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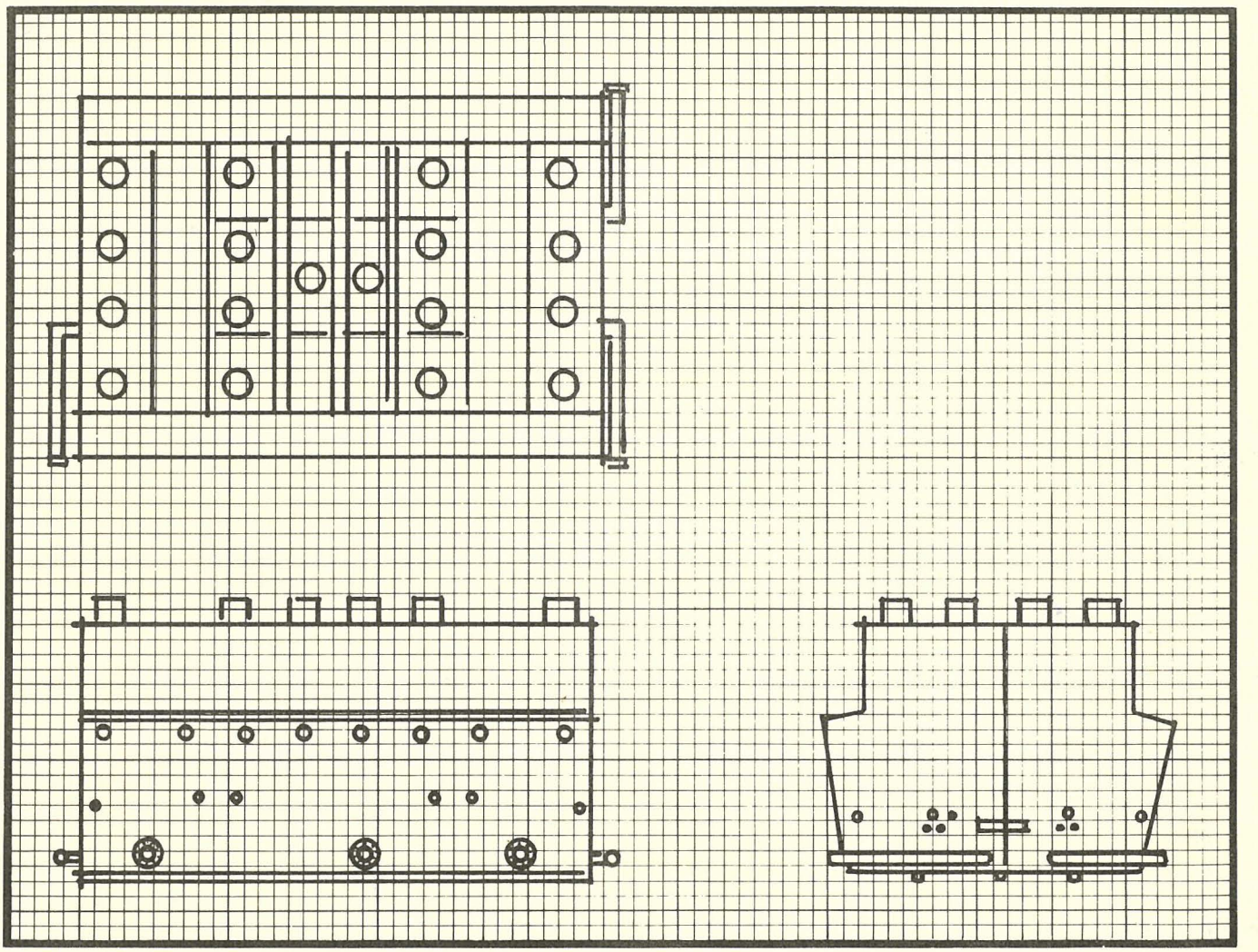
TANK DESIGN GUIDE for FIRE RETARDANT AIRCRAFT



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TANK DESIGN GUIDE FOR FIRE RETARDANT AIRCRAFT

by

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A.D. Luedecke, Honeywell Inc.

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This guide is published as a part of a program to improve fire control technology, specifically through the use of fire retardant chemicals and delivery systems whose chemical and/or design characteristics are tailored to fuel and fire situation needs. This program is being conducted at the Northern Forest Fire Laboratory. Information or questions regarding these studies should be directed to the:

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Introduction

The purpose of this document is to provide a rational basis for performance-related decisions in designing tanks for aircraft delivery of retardant. It does not deal with the modification of the aircraft to contain the tank or methods of calculating structure, weight and balance limits or other aspects of design in which airtanker contractors and operators are already well qualified. Instead, it emphasizes design aspects of the tank and its gating system to deliver an effective amount of retardant in the fire area as efficiently as possible.

Historically, air tanker contracts have been let primarily on the basis of the aircraft, its load capacity, and compliance with safety regulations. Within the limits of contract compliance there is latitude for a wide variety of tank performance based on specifics of the design and the tank builder's concept of an effective tank. This has produced a number of excellent designs and others that are less desirable. This book is intended to help tank designers with performance-related decisions and to provide them with a better understanding of what makes tanks effective.

The idea of designing a tank to optimize its performance is not new, but the information needed to pursue such designs on any but an intuitive basis is. It derives from work by the Northern Forest Fire Laboratory and others that have evolved two fundamental principles:

- **Effective retardant coverage levels on the fire fuels can be calculated to reside between 0.5 and about 4 gallons per 100 square feet depending on the fuel.** As a result, retardant delivered in excess of these amounts could be more effectively employed to generate a longer line or cover a larger area.

- **The design of the tank and the gating system can control the way in which the retardant is distributed to yield more line per mission at less cost per effective foot of line.**

Many of the illustrations in this document are drawn from 245 tests using the Experimental Tank and Gating System (ETAGS) in a U.S. Forest Service P2V-5 conducted in Chico, California, in 1975. This experimental tank was designed to simulate performance of a wide range of tanks and their variations, including tank length, volume, height, width, door speed, and compartment separation. These data are supplemented with performance information on a large numer of operational tanks separately tested by the U.S. Forest Service.

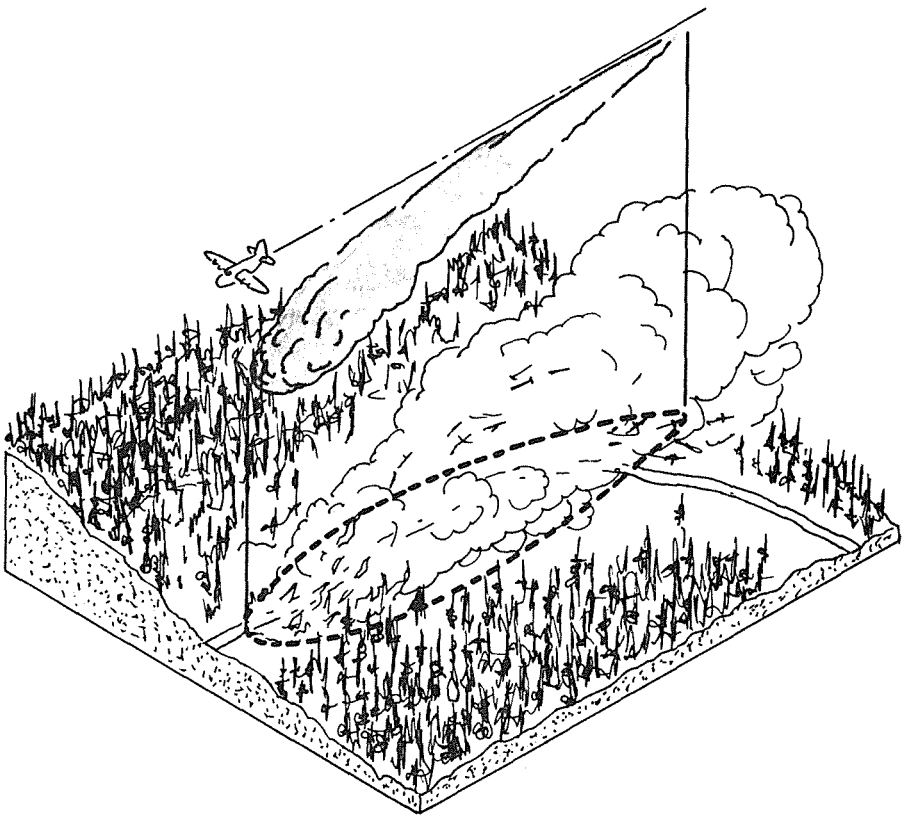
The document recommends a step-by-step design procedure with several iterations in increasing detail to optimize a tank for performance within the constraints of a specific aircraft. Each of the general procedural steps is supplemented by a specific example leading to the conceptual design of a system for the P2V-5. The example procedure shows that many of the tank's features are dictated by the aircraft, safety, ground support, and maintenance constraints rather than by the ideal of pattern generation. In recognition of this fact, the procedures presented are not intended to be presciptive to the point where the tanking contractor's skill, ingenuity and creativeness is limited but to provide additional data to aid in this process.

Theory of Airtanker Attack

The airtanker attacks the fire from the top by releasing retardant over the threatened fuels. It distributes retardant along its flight path in a manner determined by the design of the tank, aircraft speed, and altitude, and the rheological properties of the retardant. The general strategy of application is to:

- Generate as much line as necessary (or practical) at a coverage level (ground concentration) sufficient to control or reduce fire spread across the treated area, or
- Occasionally apply retardant or water to a small, spot fire.

Air operations are almost always in support of, or supported by, ground operations involving personnel and equipment. As a result, the safety of ground personnel and the tanker pilot are of highest priority in all operational phases.



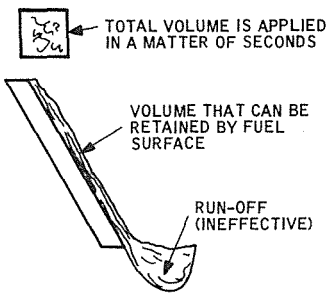
Retardant Effects on the Fire

The retardant mass released from the tank breaks up into droplets with a size distribution determined by its rheological properties. The quantity is reduced by evaporation during its fall to the fuels and impacts the fuel surfaces in the form of rain or unbroken fluid mass, depending on the stage of the breakup process.

Once on the fuels, its major effects are:

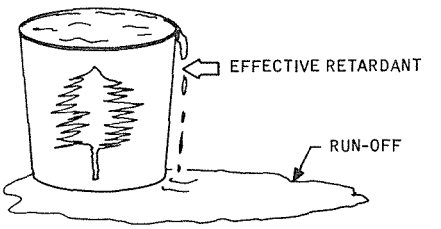
- Fuel coating (from water content and thickness).
- Fuel modification (from the retardant salts).
- Fuel cooling (from the water content).

Air delivery applies all of the retardant at once and must rely on the fuel surface to retain an adequate amount to extinguish, knock down, or retard the fire.



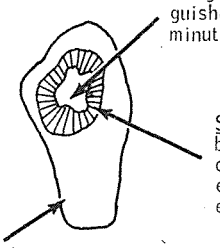
Effective volume is that retained by the fuel surface. The addition of thickening agents can increase the volume retained on the fuel and slow runoff.

Since the fuel surfaces are limited in the amount of retardant they can retain, any excess application will ultimately be lost as runoff.



This factor places practical limits on the useful coverage levels in retardant ground patterns.

It also means that, in most cases of direct attack, retardant effects on adjacent fuels are as significant as those on the reaction zone itself.



FIRE: Although dripping and running prolong the continuous effects of the brief application the total effect is limited to what can be achieved in something less than one minute -- few fires are extinguished by conventional techniques in a matter of minutes regardless of application rate.

SHORT-TERM BENEFITS: Limits of the short-term benefits of fuel cooling and coating from the water content of retained retardant. If the effect lasts long enough to resist fire spread to new fuels, delayed extinction will result.

LONG-TERM BENEFITS: The retardant salts continue to alter pyrolysis of combustion mechanisms long after the water content has been dissipated. This effect becomes more significant in aerial retardant delivery than the benefits of fuel cooling and coating from the water content of the fire alone.

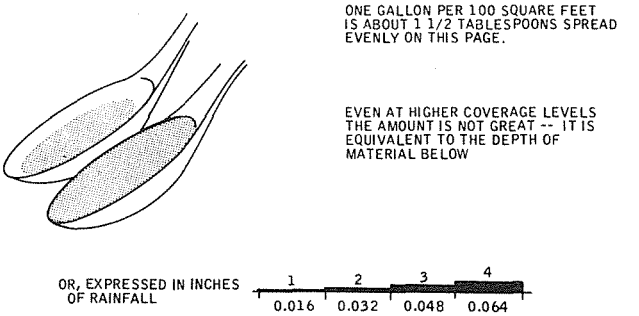
Recommended Coverage Levels

Recommended coverage levels are based on studies of fuel surface capacities, retardant salt effects, moisture damping effects, and knowledge of the pattern capabilities of aircraft known to be effective in certain fire situations. The coverage levels are related to fuel models contained in the National Fire-Danger Rating System.

Coverage Level	Recommended For:	
	Fuel Model	Description
1	A	Grasses; tundra, and open desert shrub lands
2	C	Conifer timber with grass understory
	F	Brushfields with much green material
3	D	Shrublands under 6 feet in height (such as sagebrush)
	E	Hardwood litter after leaf drop
	H	Closed conifer timber with litter only
4	B	Hard chaparral and other high (6-foot) flammable shrubs
	G	Closed, old conifer timber with litter and dead, down limb wood.
	I	Conifer slash

For creeping or smouldering fires reduction of one coverage level may be considered.

Coverage levels expressed in gallons per 100 square feet (gpc), are derived from the fuel surface area and the effect of retardant salts on spread rate in typical fuels. Coverage levels are tempered by personal knowledge of aircraft performance in certain fire situations. For example, the Bureau of Land Management has confidence in the use of trail systems against grass fires. Such systems produce considerable line at levels ranging from 0.5 to 2 gpc.

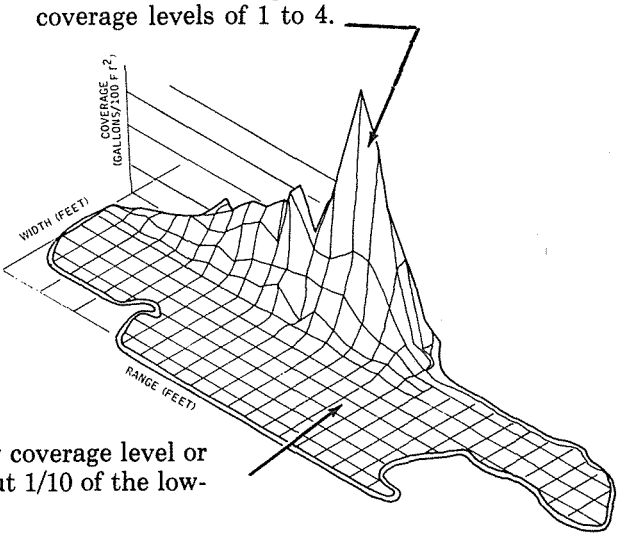

ONE GALLON PER 100 SQUARE FEET IS ABOUT 1 1/2 TABLESPOONS SPREAD EVENLY ON THIS PAGE.
EVEN AT HIGHER COVERAGE LEVELS THE AMOUNT IS NOT GREAT -- IT IS EQUIVALENT TO THE DEPTH OF MATERIAL BELOW
OR, EXPRESSED IN INCHES OF RAINFALL
1
2
3
4
0.016
0.032
0.048
0.064

Retardant Patterns

A retardant pattern maps retardant distribution on the ground in terms of effective coverage levels. The pattern provides a means for evaluating the effects of the drop on the fire/fuels by examining the area, length, and width of the pattern at its various coverage levels.

This three-dimensional representation of the retardant pattern resembles a mountain range emerging from a plateau. It shows how the coverage level, measured in gallons per 100 square feet, fluctuates over the drop area. The vertical coverage level is greatly exaggerated here.

- The mountain range contains the recommended coverage levels of 1 to 4.



- The plateau represents a very low coverage level or trace precipitation, typically about 1/10 of the lowest rcommended coverage level.

Pattern Effectiveness

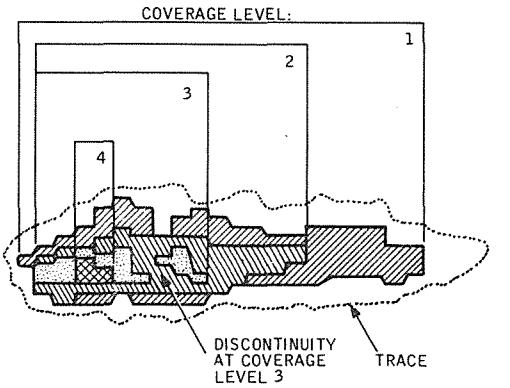
When presented in terms of an elevation map that delineates specific coverage levels, the pattern's effectiveness can be evaluated in various fire situations.

- Considerable areas of the pattern are at coverage levels in excess of that required. They are effective, but the excessive gallonage could be better used if spread over a larger area.
- Some areas are inadequately covered. They have more limited effectiveness and may in many cases be ignored.

There are three important characteristics of any pattern:

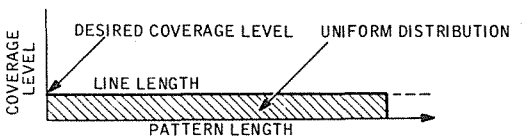
- Length at a given coverage level
- Width at a given coverage level
- The momentum of the retardant mass as it falls to the ground

These features can be controlled by elements of the tank design in association with aircraft velocity and altitude under selected delivery conditions.

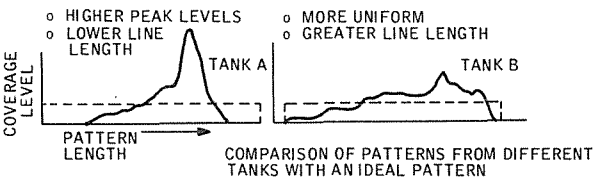


Pattern Control

The most desirable pattern occurs when the bulk of retardant is distributed uniformly along the flight path at or near the appropriate fuel coverage level.



- The uniformity of this distribution is primarily determined by the way the tank is designed, how it releases its retardant load, and the associated aircraft velocity. This is shown by the marked difference between patterns formed with equal quantity under identical release conditions with differences in the tank design.



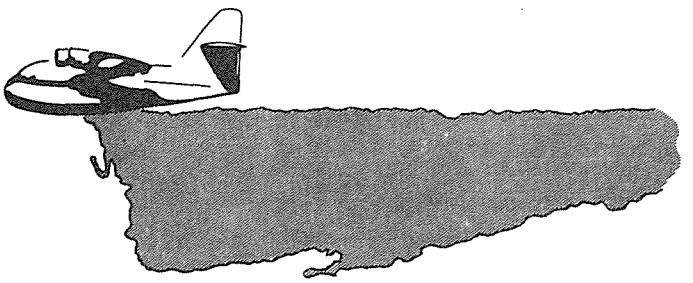
- The coverage level achieved is determined primarily by the quantity of retardant released in this way, the height of the aircraft at release and the type of retardant employed.
- Additional control of distribution and coverage level can be achieved by the judicious use of the gating system and the addition of retardant quantity from separate tank compartments simultaneously or in sequence.

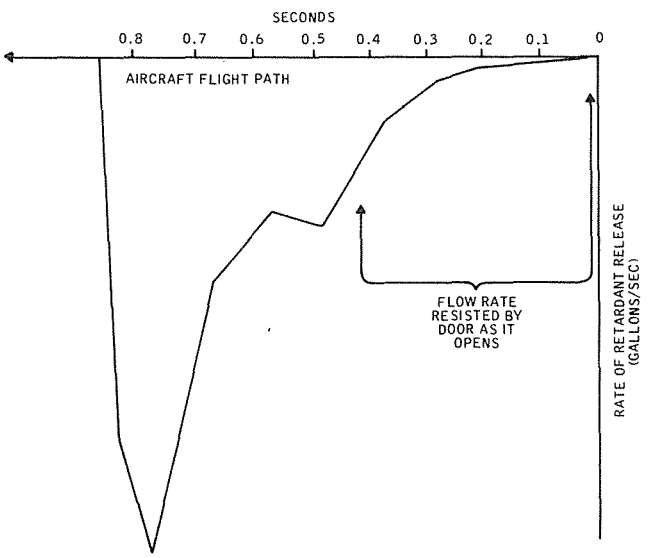
These methods of control and their effect on retardant are the subject of the following pages.

Flow-Rate Management

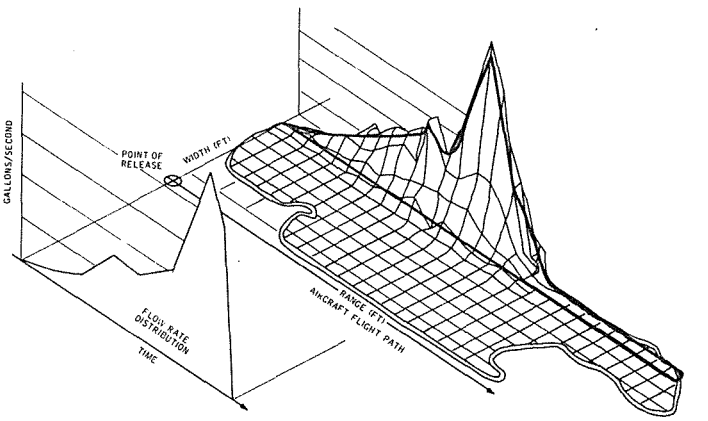
Volume flow rate from the tank is the primary determinant of the retardant distribution pattern. The tank exit geometry or door configuration establishes the aerodynamic properties of the released fluid to change the distribution. Aircraft velocity, altitude, and retardant type simply modify the resulting retardant distribution on the ground.

The flow rate from the CL-215, for example, has the basic form shown below, which is determined by tank geometry, door opening rate, venting, and door area.





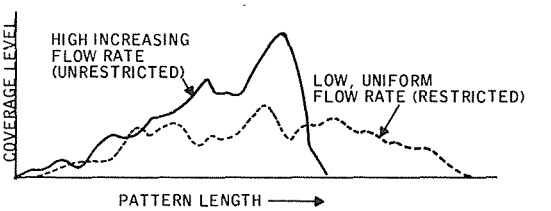
The three-dimensional plot below shows how flow-rate distribution is reflected in the ground-coverage pattern.



Flow rate is determined in the tank design by:

- Height of the fluid head
- Area of the open door
- Geometry of the tank
- Door opening rate
- Tank venting

Control of the flow-rate distribution can change patterns substantially.



These patterns from tanks of equal volume at identical release conditions illustrate the difference between a free-fall fluid release and a restricted tank release. Understanding and management of these two release types provide leverage on pattern improvement.

Flow-Rate Effects on Ground Pattern

Studies on a wide range of actual airtankers and analysis of the ETAGS test results confirm that there are two types of tanks in general use. They can be categorized by their flow rate in two ways. First, the average flow rate can be related to the average level of retardant ground coverage. Second, the flow rate distribution can be related to the way coverage on the ground varies around the average. In the following pages three types of tank performance, each yielding different flow rate distributions are discussed:

- **Free-Fall Flow** — The gallons per second released from the tank start slowly and increase rapidly throughout the evacuation. Patterns are not usually uniform, but contain large areas that are well over and other areas considerably under the desired level. Several tanking systems fit this class.

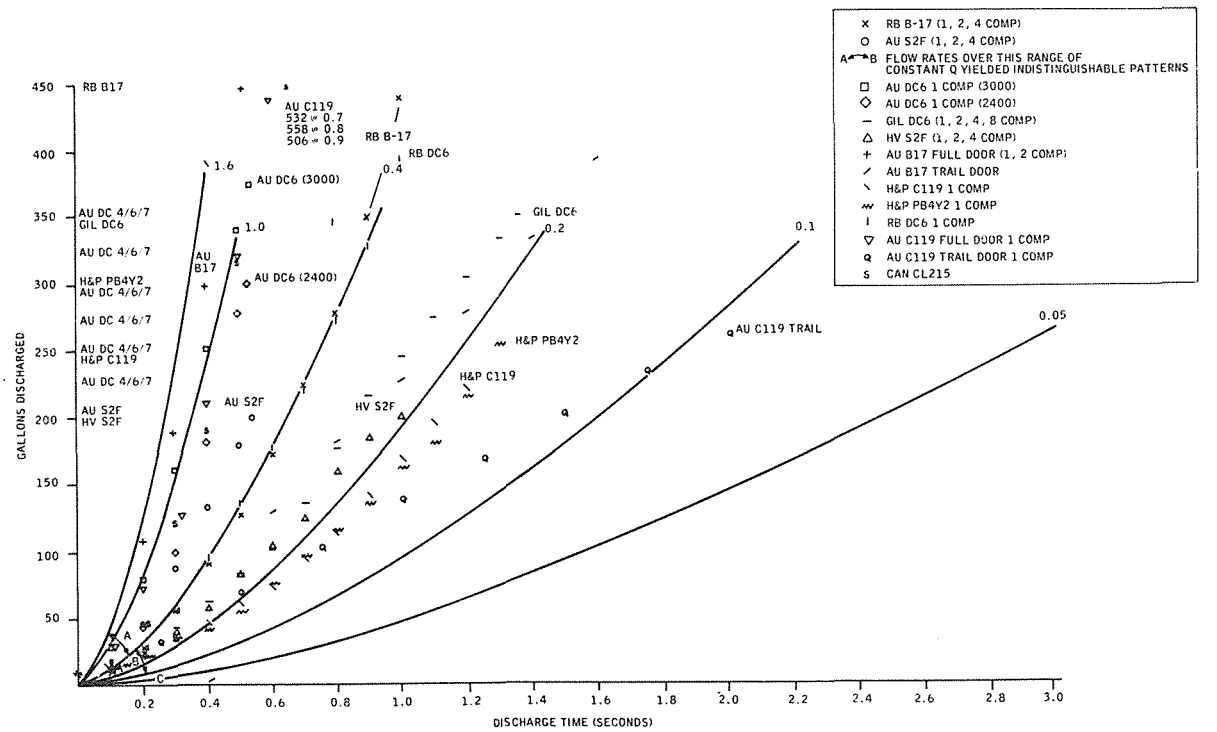
- **Restricted-Flow** — The gallons per second released from the tank start slowly, reach a peak, then decline slowly to evacuation. Patterns are more uniform, tending to group around the average coverage level. A few tanking systems fit this class.

- **Combinations** — Many tanking systems work in a region that is partly established by free flow and partly by restrictions. These patterns are generally considered from the standpoint of the analyst as superior in that they tend to maximize the fireline at their characteristic level.

Scatter data indicating the three distinct ranges of tank performances are shown in the accompanying figure.

From ETAGS studies, an appropriate relationship between the average flow rate (tank-determined) and the average coverage level on the ground can be established. The values are approximate in that other factors such as tank configuration drop speed and retardant type can change them. Nonetheless, they are useful in estimating tank parameters.

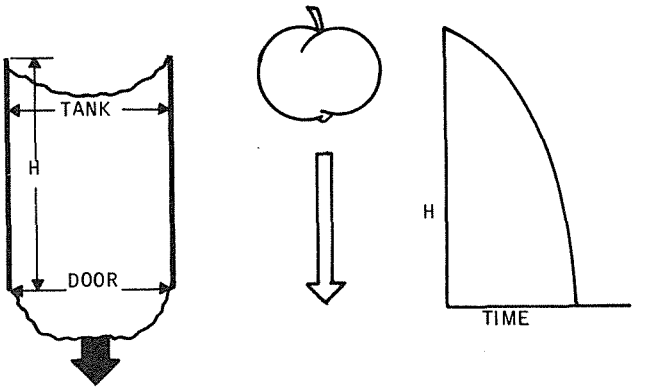
In a series of tests with a tank yielding a near uniform flow rate, it was found that a gum-thickened retardant (Phos-Chek XA) produced a coverage level of 1 at an average flow rate of about 200 gal/sec. With water, the coverge level of 1 was not achieved until the flow rate was about 100 gal/sec higher. The increase in coverage level is nearly linear with flow rate such that Phos-Chek XA drops at 396 gal/sec yield coverage levels of about 1.9. This is well into the C range of tanks shown in the figure.



Evacuation from an Unrestricted Tank

The Newtonian free-fall equations are used to describe flow from a tank without restrictions. The velocity of fluid out the bottom is determined by gravity and time:

V = velocity = gt



A FREE-FALL TANK IS NOT RESTRICTED BY DOORS OR CHANGES IN TANK GEOMETRY

Since the product of velocity and door area is a volume flow rate (cubic feet per second), the flow rate continually increases to tank evacuation. The pattern it produces, also exhibits a continuously increasing level. Useful equations in designing this form of tank are:

V_E = peak fluid velocity = $\sqrt{2gH}$

T_E = time to evacuate = $\frac{2H}{g}$

Q_p = peak flow rate = $V_E A_{door}$

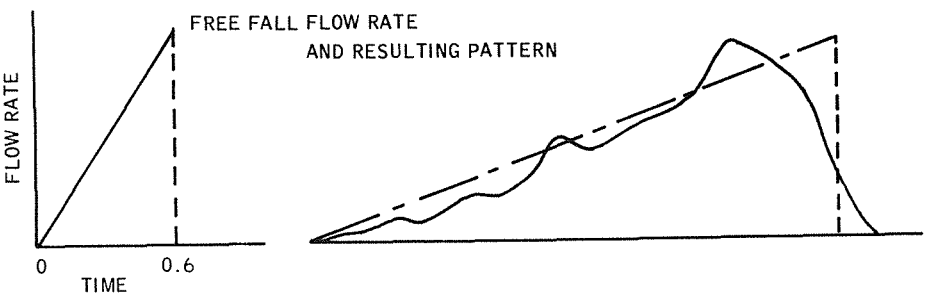
Q_A = average flow rate = $\frac{V_E A_{door}}{2}$

H = fluid height

If the inflow of air through the tank vents is insufficient to replace the volume of fluid evacuated, a negative pressure will develop, causing a decrease in the evacuation rate. When provisions for estimating this pressure are included, the velocity is affected by the equation:

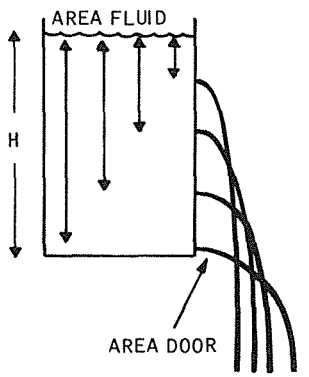
$$V = gt\left(1 + \frac{P}{\rho H}\right)$$

where pressure (P) is negative and in the same units as the fluid pressure (ρH), and ρ is the retardant density.



Evacuation from a Restricted Tank

The Bernoulli velocity equation is employed to describe fluid evacuation from a restricted tank.



It is used to describe the water drainage from a punctured can. The equation asserts that velocity (in a slowly changing situation) is determined by the fluid head:

$$V_B = \sqrt{2\,gH + V_Z^2}$$

Where V_Z is any velocity imparted to the fluid before the conditions of restriction arise. For the slowly draining tank, this equation implies a continuously decreasing velocity and flow rate. In practice, even restricted tanking systems have rapid rather than slow drainage. As a result, typical restricted flow starts with a brief acceleration phase that builds up to the peak velocity predicted by free-fall equations, then trails off slowly following the Bernoulli Rule.

The time out of tank for a restricted tank is:

$$T_E = \text{time to evacuate} \approx \frac{A_{fluid}}{A_{door}}\sqrt{\frac{2H}{g}}$$

$$V_E = \text{peak fluid velocity} = \frac{A_{door}\sqrt{2gH}}{A_{fluid}}$$

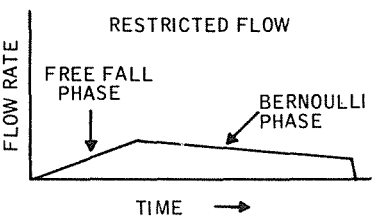
$$Q_p = \text{peak flow rate} = V_E\, A_{door}$$

$$Q_{ave}\ \text{S}\ \frac{\text{Quantity}}{T_E}$$

If negative pressures result from venting, the velocity can be estimated from

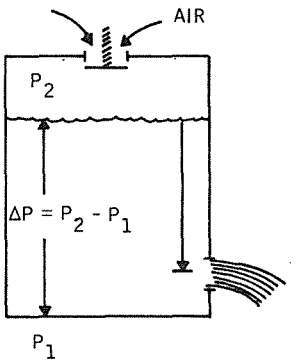
$$V_B = \sqrt{2h\,(H + 2.3P) + V_Z^2}$$

where pressure (psi) is negative.

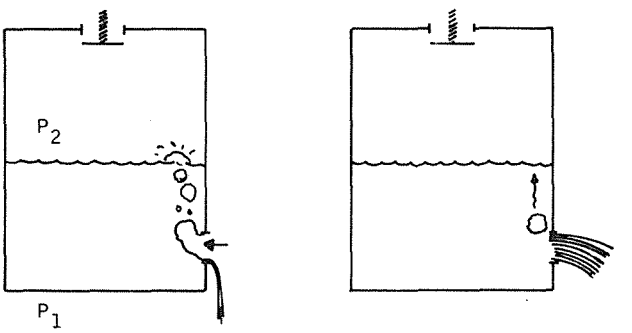


If the inflow of air through the vent at the top of the tank is insufficient to replace the volume of fluid evacuated, a negative pressure will develop causing the velocity of fluid evacuation to decrease.

If the air replacement rate is severely restricted, the pressure head will soon equal the flow head, and the tank will "stop" or in the more normal case, start to "pop-bottle."



In pop-bottling the pressure is relieved by air inflow from the bottom in the form of bubbles, with the tank oscillating between fluid moving out and air moving in.



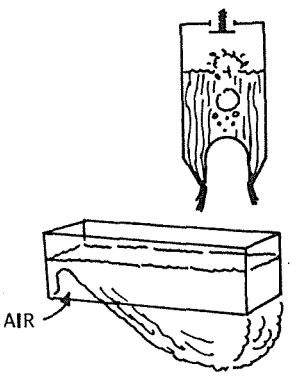
In a retardant tank this takes the form of rather large bubbles, while limited flow occurs around the sides.

Because, when this situation occurs, flow is not only reduced but becomes erratic, ground pattern performance is similarly affected. As a result, the conditions of pop-bottling must be prevented in designing the tank and specifically its venting system.

The amount of pressure that develops and its effect on retardant flow is difficult to ascertain simply. The peak pressure that will occur in a tank can be estimated, however, from the following equation:

$$\text{Pressure (psi)} = 1.33 \times 10^{-5} \left(V_E \frac{A_{door}}{A_{vent}}\right)^2$$

This shows the importance of adequate vent area to prevent adverse consequences on flow rate. Specifically, the pressure must never equal the velocity head.



Tank Exit Geometry Effects on Ground Pattern

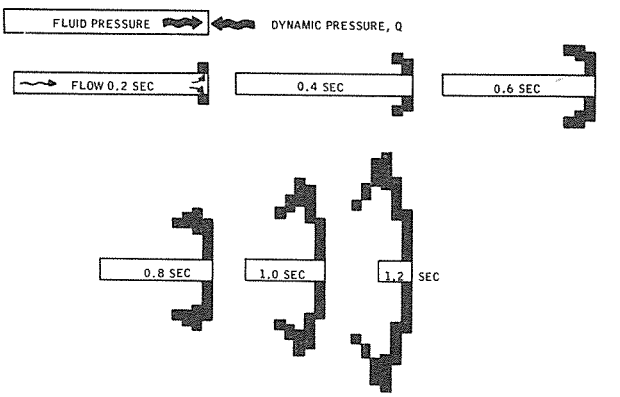
The second tank characteristic that determines pattern formation is the door geometry that forms the aerodynamic shape of the retardant as it is released. This shape determines the rate of retardant breakup as it flies downrange.

If a fluid column is released into air with a forward velocity, it is resisted by the relative wind. If it were solid it would be slowed by frontal (and skin) drag; but an unrestrained fluid has no strength and must collapse, displacing fluid laterally from the front. The column will collapse similarly to the stream from a hose splashing against a soft, receding wall.

The equations governing this action show that the deceleration at the front of the column is determined by the dynamic air pressure, Q, and the fluid pressure, ρL, (density $\times$ length), or

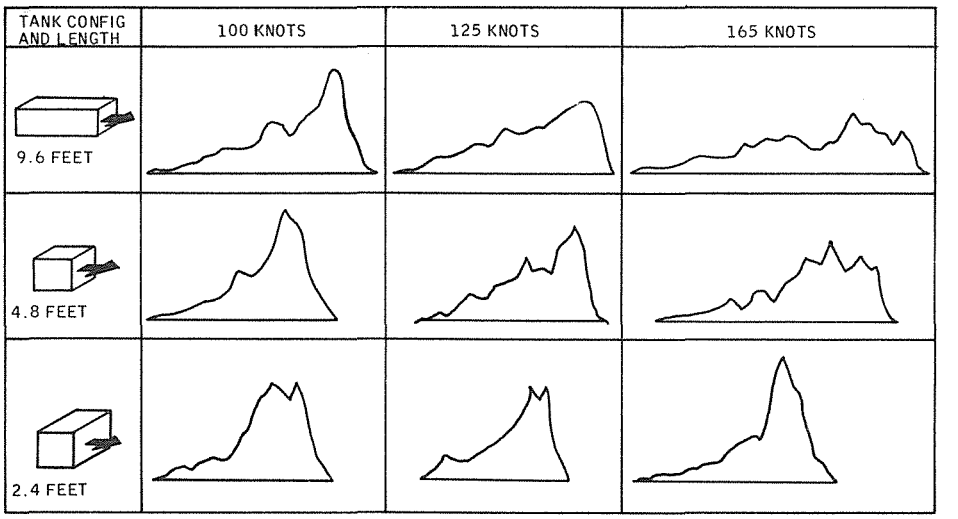
$$a = \frac{Qpsi\ G}{\rho L} \quad \text{or} \quad \frac{\rho_{air}\ V^2}{\rho L}$$

These equations show that the rate of fluid breakup is highly dependent on aircraft velocity and mildly dependent on the factors, familiar to pilots, affecting air density. It accounts for a reported tendency of experienced pilots to overshoot aim points at high altitudes and suggests slightly slower breakup (longer flight trajectories) for more dense retardants. From the tank designer's standpoint, it shows the effect of door length on retardant breakup.



Velocity and length effects are shown on the pattern cross sections from ETAGS tests for tanks released at the same quantity and flow rate but with different exit geometries.

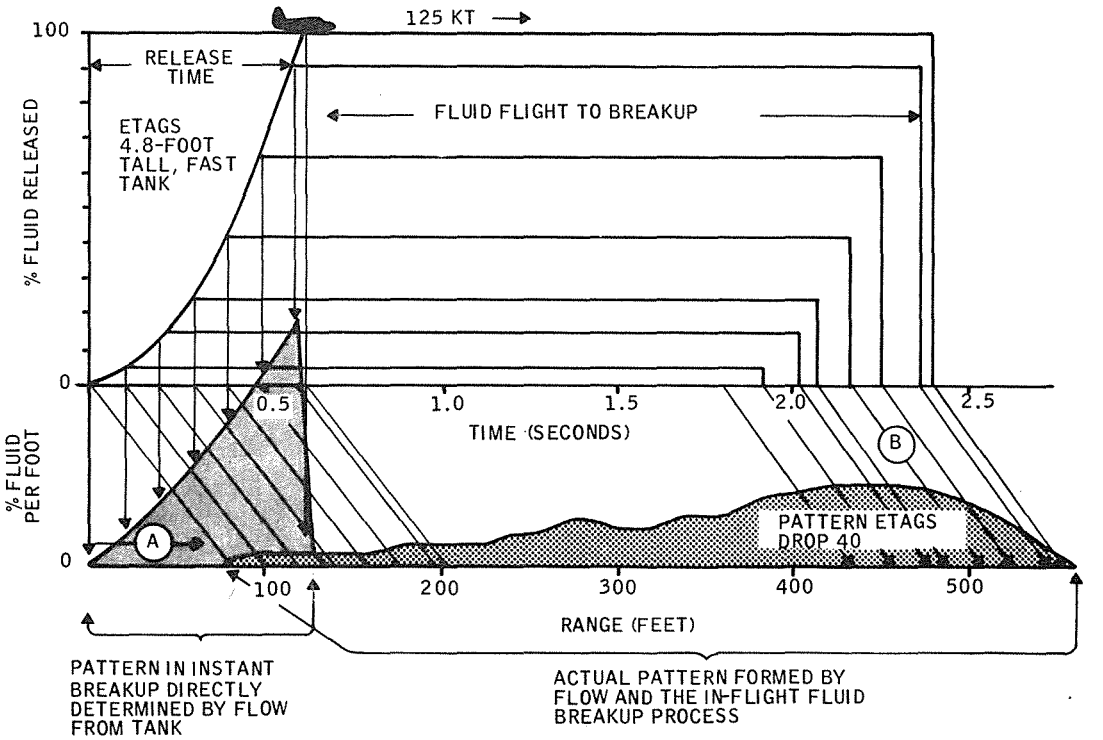
In general, the well-distributed patterns derive from drops with the longer retardant mass geometries. These patterns are, however, more strongly sensitive to the effect of aircraft velocity. The commonly held belief that retardant drops should be at or near stall velocities probably derives from experience with the very long doors of the TBMs and their low retardant capacity. Tanks of moderate length (4 to 6 feet) show little velocity-dependence in their pattern performance. In general, an adequately tanked aircraft can develop effective patterns at safe power levels up to about 170 knots before airspeed begins to degrade patterns significantly.



Flow Rate and Configuration

Flow-rate and configuration factors combine to determine the pattern distribution and coverage levels in a way that is complex and difficult to model or visualize. The concepts are best shown by mapping the flow rate from a measured drop into the pattern range distribution as shown in the accompanying illustration.

- If the fluid breaks up immediately on release from the tank, the distribution is almost entirely defined by the flow rate. (This condition of immediate breakup will occur when the length of fluid released is about 1.5 feet long with respect to the aircraft flight path or with drops at a very low flow rate.)
- If tank evacuation is exceedingly short (low-head tanks) the distribution is almost entirely determined by retardant breakup in flight and the inertial characteristics of breakup products.
- Most patterns, however, represent the combination of effects shown, where flow rate organizes the retardant mass distribution for flight. It then travels downrange, distributing retardant by length-decay mechanisms until the retardant column equals the counteracting dynamic pressure. At this point, instabilities develop on the front (the familiar corrugations seen in most drops) to shatter the remaining mass.



Ⓐ = APPROXIMATE INERTIAL TRAVEL OF BREAKUP PRODUCTS FOR EACH TANK INCREMENT
Ⓑ = APPROXIMATE END POINT OF EACH TANK INCREMENT

Coverage-Level Control

Since coverage levels for most fuels range from about 1 to 4 gallons per 100 square feet (gpc), an effective tank should be able, on command, to deliver a maximum amount of retardant line at each of the specified levels. This means it is desirable to deliver uniform distributions at four different coverage levels.

There are four basic ways of controlling the coverage level and a wide range of combinations:

- Use of fixed-flow compartments dropped in sequence or combination
- Use of door options on one or more compartments
- Use of door dynamics to control flow-rate
- Inventive combination schemes

Each of these is discussed in the following paragraphs.

Compartment Addition — The use of multiple, separately releasable compartments, each performing similarly, allows the addition of quantity by sequential or simultaneous release to achieve a range of desirable coverage levels. In principle, the unitary compartment is designed to produce a repeatable, near-uniform pattern providing maximum line length at a coverage level of 1 under nominal drop heights (~150 feet above fuels). To double the coverage level, the patterns from two compartments are overlayed by releasing them simultaneously. Division of a tank into at least four such compartments will provide tailored coverage in nearly all fire/fuel situations (1, 2 or 4 gpc).

The selection of compartmentalization schemes will depend, in part, on the anticipated usage of the aircraft against specific fire fuel situations and on design factors.

Compartmentalization Analysis — If high-priority fire situations require a coverage level of four and this coverage level can be achieved by the load capacity of the aircraft (typically more than 800 gallons), the tank will be divided into not less than four compartments, with additional compartments added in increments of four. We will assume this case for the P2V examples. With this mission requirement, a tank with six compartments would be less than optimum, allowing the drop of one pattern at coverage level 4 (four compartments), with a residual drop capability of one pattern at coverage level 2.

If the major mission spectrum involves fire situations requiring level 1 or 2 coverage, compartmentalization may be limited to multiples of two. This is a good practice for smaller tanks where the ability to deliver at a coverage level of 4 is limited in any case. In this case, a six-compartment organization would provide increased flexibility in selecting appropriate low-coverage line lengths.

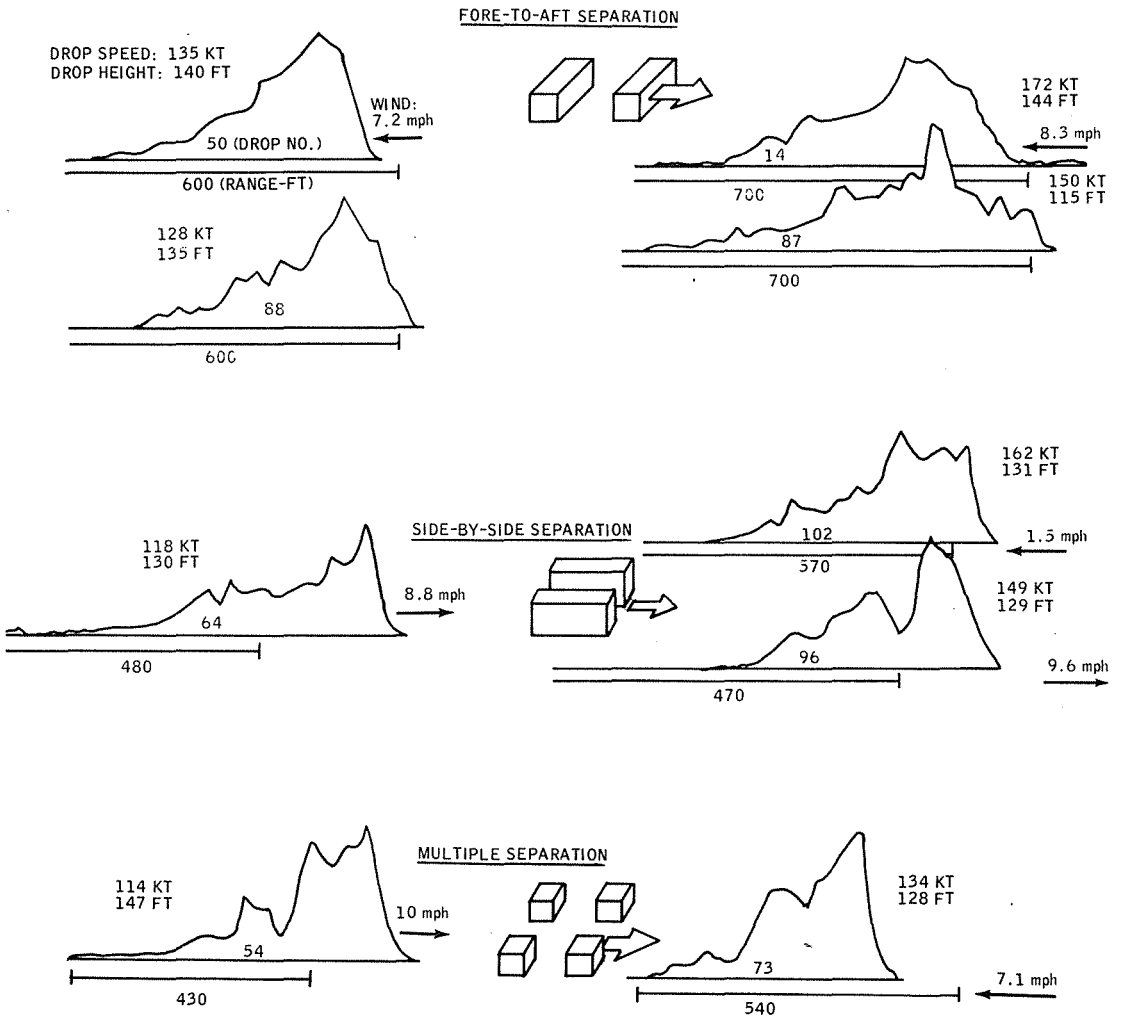
In considering the optimization of a tank for more specialized usage profiles, many other possibilities arise in compartmentalization and the selection of tank control techniques. In current practice, regional specialization is not encouraged due to the necessity of marshalling resources as they may be available in critical fire areas. There are some instances where tanks have been effectively specialized to the predominant fuel types (notably for the BLM in regions dominated by grass fires). Intelligent experimentation in this area should be encouraged, provided that the tank can be returned to a more conventional configuration as contracts or out-of-region requirements arise.

Compartmentalization of the Example Tank — The 2460-gallon P2V tank will contain not less than four compartments with additional compartments limited to multiples of four compartments. The large retardant capacity makes such division practical and preserves maximum flexibility in all fire/fuel situations.

Compartment Separation

The addition of quantities delivered simultaneously from separated compartments places some limits on the tank's division. If possible, addition from neighboring rather than separated compartments is desirable. (This feature cannot always be preserved since the order of compartment releases is often determined by the retardant loading scheme and, occasionally, by the need to preserve aircraft trim.)

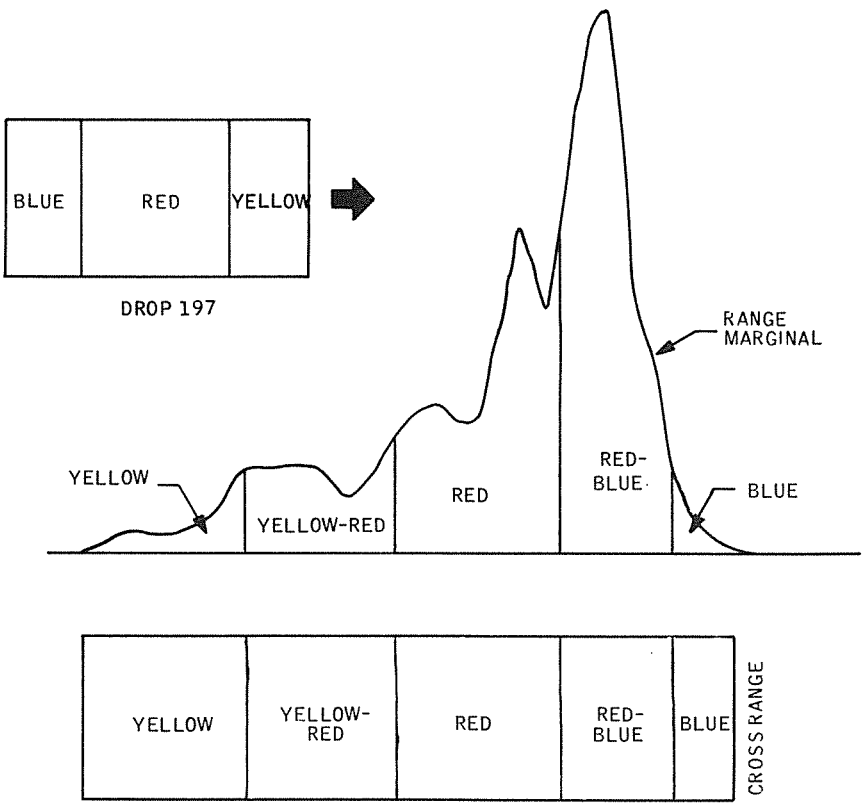
If compartment drops must be separated, the least number of intervening compartments should be preserved, fore-to-aft separation (along the direction of flight) will generate more line at or near the desired coverage level than compartments separated across the width of the aircraft. Multiple separations in a planned drop will not produce adequate patterns and should not be used.



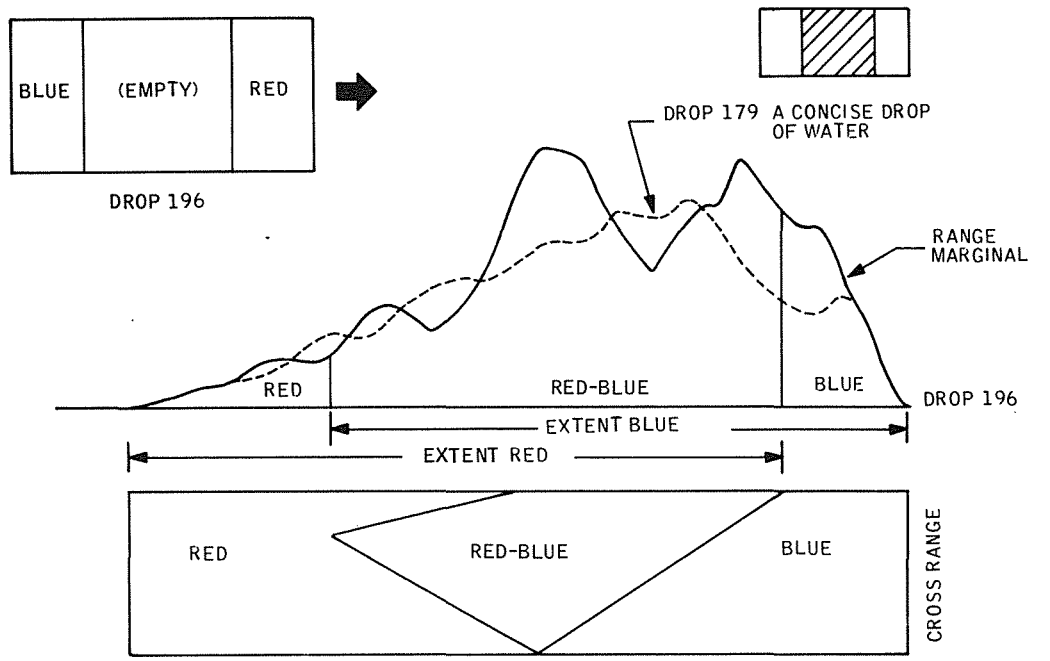
Mixing Phenomena

Mixing of retardant between compartments was examined in a series of tests during the ETAGS program, using pigmented water to determine colorimetrically the degree and extent of mixing under various conditions.

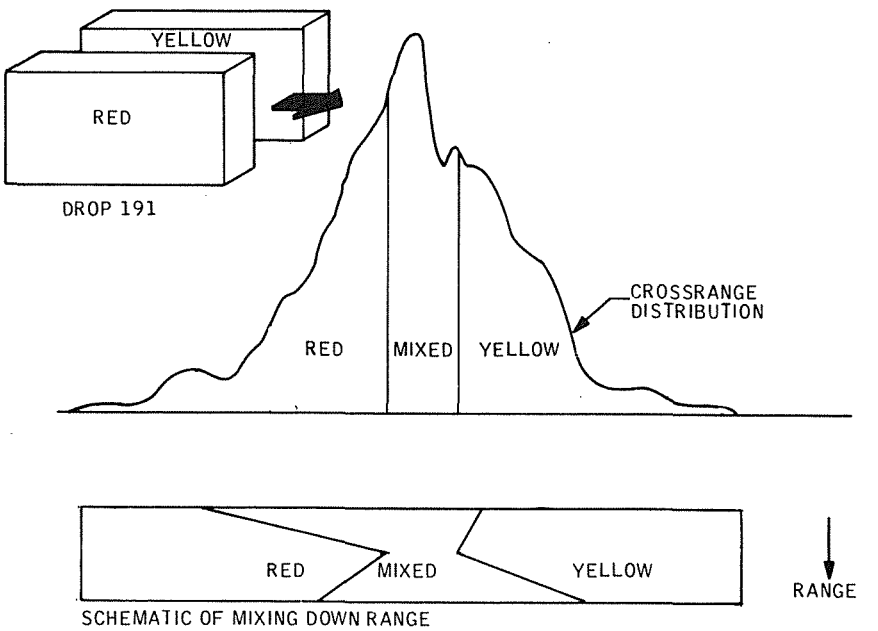
Contingent fore-to-aft addition (below) roughly doubles the tank length. This increases pattern length about 20 percent. Coverage level will then increase by about 1.7 times (not 2 as would be expected in full addition). (Note that the breakup process inverts the fluid with respect to its position in the tank. The front of the tank forms the rear of the pattern.)



Separated fore-to-aft compartments can generate patterns similar to those achieved by sequential release. In this drop, camera coverage and pattern showed that the rear compartment fluid was protected from dynamic forces until the forward fluid was stripped away.



Mixing from side-to-side separation yields overlapping individual patterns that are not necessarily additive unless the compartments are truly neighboring. The addition shown is also about 1.6 times the coverage level rather than the two from formal combination.

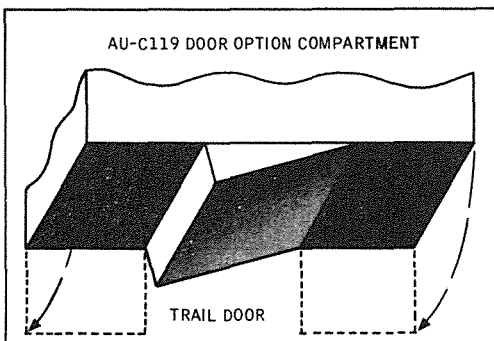


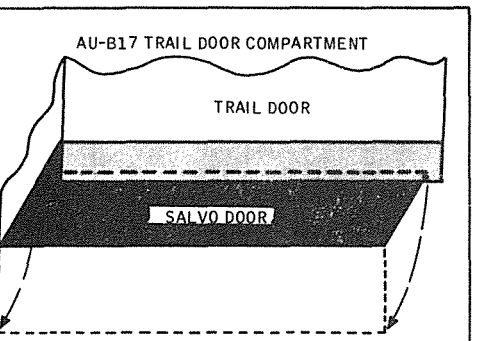
Use of Door Options

Door options have been used effectively in two Aero Union aircraft to provide controllable selection of low- or high-level patterns. These systems use, in addition to the standard doors or gates, separately openable small doors (B17) or chutes (C119) that considerably restrict the fluid flow.

A system using only multiple doors to control flow will usually be limited to a tall tank with restricted width and length dimensions, since the ability to realize its control is limited by the distance the fluid must travel across the tank to reach the exit as well as the restriction on its movement caused by baffling.

Some limitations on the effectiveness of this technique should be noted. Restriction for coverage level 1 will produce a Bernoulli-like flow yielding good uniformity. As the door area becomes larger, the flow rate becomes more abrupt, yielding triangular pattern distributions that depart from uniform. This control technique is best when tank capacity is sufficiently low that coverage levels of 4 are difficult to achieve under any conditions. Thus, uniform low-level line, reasonably efficient moderate-level line, and some high-level line can still be achieved. This is applicable for aircraft capacities from 500 to about 800 gallons.





COVERAGE LEVEL	DOOR	COMPARTMENTS	DOOR	COMPARTMENTS
0.5	TRAIL	1	TRAIL	1
1	TRAIL	2	TRAIL	1
2	SALVO	2	SALVO	1
4	SALVO	4	SALVO	2

Use of Door Control

Door control of flow rate was demonstrated in the ETAGS program and has been found to exist inadvertently as a flow modulator on several airtankers in which door opening slows as the number of doors operated increases. Although, in theory, a door could be stopped to provide any desired area, this is usually difficult to accomplish since snubbing at the end of a power stroke (to prevent door structural damage) is best accomplished by the hydraulic (or pneumatic) cylinders. As a result, control of opening rate (area development) rather than open angle is more appropriate. To achieve the range of rates desired, very long door-opening times must be provided, a rigid door is required, considerable cylinder area must be included to hold against flow, and large area control lines are required to provide adequate control fluid for the fast rates. The major advantage—that the system can provide virtually unlimited control of flow rate—is partly offset by additional complexity. Although there is room for considerable inventiveness in the use and design of such a system mechanically, the amounts required in a given fire situation are not as yet refined to the accuracy that could take advantage of more precise tank control. Thus, as a practical matter, the use of only two rates (fast and very slow) on each of two compartments appears to be the most desirable option for current consideration. Although, theoretically, the dual rate yields three door opening rates (fast only, slow only, fast and slow), the rate differences for effective control are sufficiently large that the combined rate will be very little different than the fast rate.

Use of Combinations

There are a relatively large number of combinatorial schemes for employing the three basic methods of flow control. They are generally compatible, but the rules of combination depend on the tank's configuration, capacity, aircraft cg shift limits, and, to a lesser extent, the design of a compartment loading system.

Tank Design Procedure

The following steps are recommended as guidelines to developing a tank design. Examples are shown relative to a P2V-5 aircraft.

(1) Visually examine the aircraft and determine the space available for tank placement. Measurements should be made of the approximate available volume (length, width, and height) and possible tank attachment points. A rough sketch of the available volume (or of a tank geometry which could be fitted into this volume) should be made. Measurements for determination of tank ground clearance should also be made at this time. Where external tanking is possible, ground clearance, aircraft center of gravity and structural hardpoints should be noted. Major benefits are possible for external tanks in that design and performance of the tank need not be restricted by peculiarities of the aircraft's external structure.

(2) For the particular aircraft, determine the approximate maximum load weight (retardant and tank) which can be carried. Convert this weight into gallons, either by assuming a retardant plus tank weight of approximately 10 pounds per gallon (assume the retardant weighs about 9 lb/gal. and the tank structure about 1 lb/gal.) or by estimating a completed tank weight.

(3) Determine the approximate retardant volume (in gallons) which could be carried, based on a tank geometry which could be fitted into or under the aircraft. The smaller of the two gallonage numbers determined in (1) and (2) above will be the approximate capacity of the tank.

(4) Make a rough sketch of the geometry of the tank which will fit into the available volume and meet the gallons limitation of (3) above.

(5) Compute the number of possible compartments, assuming approximately 300 to 600 gallons per compartment, and determine approximate compartment configurations which can be packaged within the tank external geometry. (Note: Size adequacy will depend on what flow control system is being used. The minimum compartment should not be less than 200 gallons at the maximum off-loaded condition.)

(6) Estimate the door dimensions and locations and evaluate door plans.

(7) Design the tank filling and off-loading system.

(8) Determine ground clearance.

(9) Design the door-opening system.

(10) Design the tank venting system.

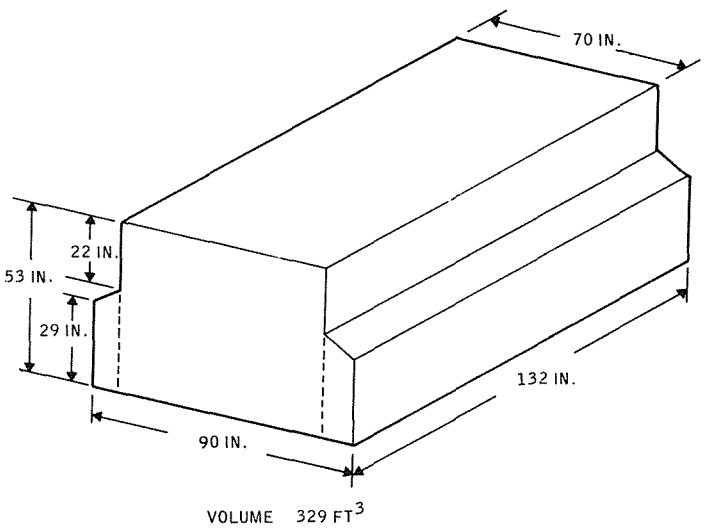
(11) Elaborate the design to include structure and construction considerations and reiterate the design process in increasing detail until the tank is satisfactory.

Step 1 — Determine Available Tank Volume

Locate the volume of the aircraft to be allocated to tank installation. The volume centroid should be closely aligned with the aircraft center of gravity. Identify aircraft primary structure related to the available volume that might restrict tank installation or venting. Also identify structural hard points for mounting.

Develop a volume envelope describing the available space, and estimate the cubic feet (volume).

For the example design of the P2V-5, the initial envelope sketch is shown. The length corresponds to the bomb-bay in the fuselage. The side panels represent a reasonable extension outside the body lines. Shape limits come from unalterable structure. In many cases, as in high-fuselage commercial aircraft, the allowable volume is virtually unlimited.



Step 2 — Estimate Aircraft Payload

Determine the aircraft payload limits in pounds. It is desirable to use the landing limit so that retardant can be returned to base if the drop should be aborted.

Divide the payload weight by 10 to estimate tank capacity in gallons. This value allows about 1 pound per gallon for tank hardware.

Divide the estimated gallons by 7.48 to determine the weight-limited volume in cubic feet (weight).

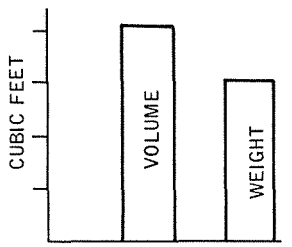
For the P2V example, the gross payload is about 25,000 pounds. If we budget 2000 pounds for tank structure, 23,000 pounds are available for retardant. This results in the following:

Retardant Type	Lb/Gal.	Gallons/23,000 lb
Water	8.337	2760
Phos-Chek XA	8.921	2580
Fire-Trol 931-L (LC)	9.096	2528
Fire-Trol 100	9.479	2430

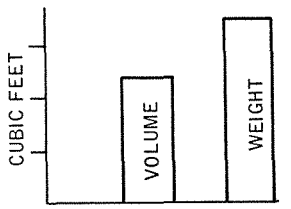
Step 3 — Determine Volume/Weight Tradeoff

Comparison of the volume limits with weight limits creates one of three situations:

- Cubic feet (volume) exceeds cubic feet (weight) — This condition exists for most externally slung tanks and some other larger aircraft. In this case, establish dimensional limitations. Usually either height, width or both are limiting dimensions, with considerable freedom existing in length as long as it is approximately centered on the aircraft cg.

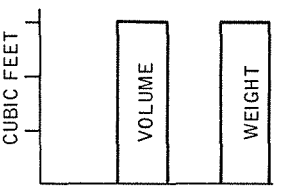


- Cubic feet (volume) is less than cubic feet (weight) — Look to the possibility of extending the fuselage line to build the tank closer to the weight limit. Some extension below the streamlines on an aircraft are usually acceptable and must be judged in terms of their increase in drag and the consequent effect of flight performance of the specific aircraft. In general, the frontal cross section should be minimized.



A second limit may be more severe, arising from ground clearance under normal as well as emergency landing conditions. As a minimum condition, the doors must be able to open on the ground. Since door closure is a part of an operating system that could fail, they **must** clear the ground when landing with the door open. It is desirable, if not mandatory, for the doors to clear the runway during tail-down landings, landings with one strut compressed or a combination of both situations. If these conditions cannot be satisfied, the effect of such a landing on aircraft safety must be carefully considered.

- Cubic feet (volume) equals cubic feet (weight) — Here the tank design problem is greatly simplified—it is basically to make the best tank we can within the space available. The P2V example fits this case:



$$\text{Volume capacity} = 329.2\ \text{ft}^3 \times 7.481\ \frac{\text{gallon}}{\text{ft}^3}$$
$$= 2460\ \text{gallons}$$

Weight capacity = 2430 gallons of Fire-Trol

Step 4 — Establish a Baseline Configuration

Sketch the results of Step 3. This is the time to note structural support points, refine measurements, do preliminary weight/balance estimates, and evaluate structural modifications, if any. This baseline will be further examined and changed as decisions on other construction and design details are evolved. For the P2V example, the volumetric baseline closely approximates the weight baseline. As a result, the volume envelope stands.

Step 5 — Compartmentalize the Tank

Airtanker requirements specify compartments containing not less than 200 gallons nor larger than 600 gallons unless flow rate is adequately controlled by door opening size or rate.

Tank compartmentalization employs a number of rules relating to the theory expressed in the preceding pages. The decisions are best illustrated by the P2V example. The 2460-gallon tank can be compartmentalized in several ways. For maximum flexibility, we will use no less than four and limit selection to multiples of four compartments.

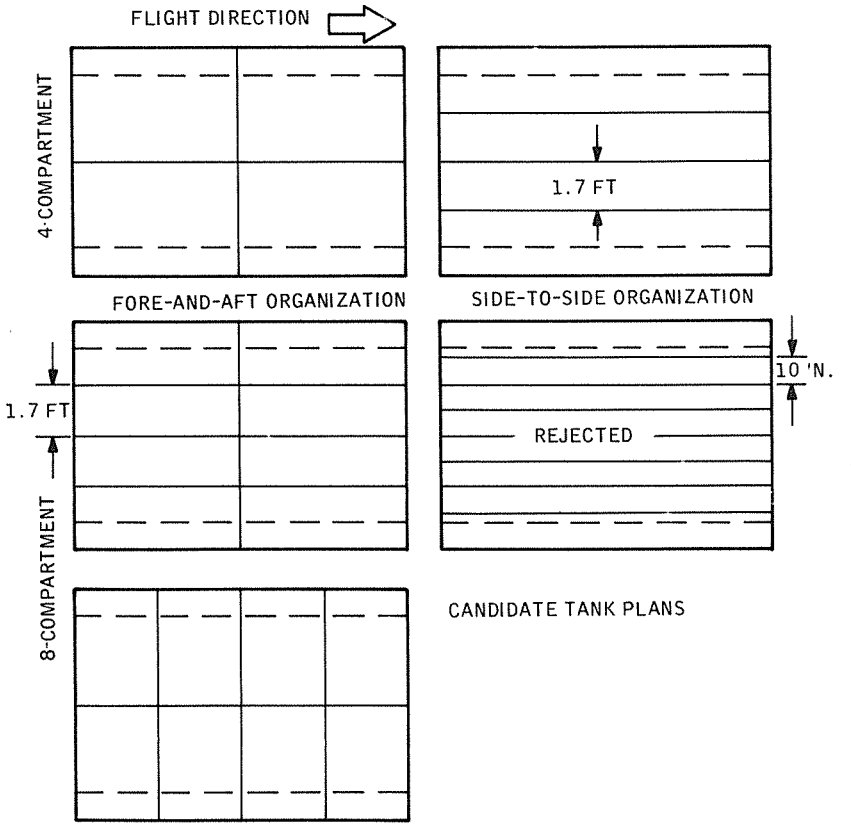
Possible divisions are:

Compartments	Gallons per Comp.	Downloaded 60%	Minimum Flood Rate for 6-sec Safe Release	Approximate Rate to Provide Coverage
4	615	369	102.5	107
8	307	184	51.2	107
12	205	123	34.2	107

Although the P2V has sufficient power that severe downloading (60%) will not normally be required, the download limit should be considered in compartmentalization decisions. Safety regulations require tank evacuation within 6 seconds. This value must be preserved. It mitigates against selection of a very large compartment since the resulting minimum flow rate will be excessive for low coverage levels. Note that the 12-compartment tank is clearly marginal, both in terms of quantity and complexity. Four- and eight-compartment configurations bear further examination.

Some viable tank plans should then be sketched for evaluation as shown. Note that the fuselage clearance in the example creates some unique problems, in that only two tank organizations provide identical compartments. Each of these plans provides adequate tank length with respect to the flight path, although the 4 long by 2 wide organization yields considerably less length than we would like.

The eight-tank plan with cross aircraft organization is marginal because the 10-inch width makes maintenance and inspection of the internal structure difficult. The very limited space also creates problems in the design of a door drive mechanism.



Step 6 — Estimate Door Dimensions and Area and Evaluate Door Plans

Door decisions determine both exit geometry and flow-rate distributions. The tank design hypothesis utilizes addition of quantities from separate compartments to achieve a full coverage range. Therefore, the flow from a single compartment should produce an average rate, at nominal flight conditions, yielding a coverage level of 1. We know, however, that quantity added from separate compartments falls short of 2 times the rate from a single compartment. Let us assume that the coverage level of 2 will be the normal delivery mode. Allowing a safe drop height clearance of 150 feet, the combined average flow should be about 440 gal/sec for a gum-thickened retardant. The rate of a single compartment to preserve the addition rule (combined coverage $\approx$1.66 single coverage) will be 440/1.66 or about 265 gal/sec. Four-compartment salvos would then deliver at an effective rate of about 730 gal/sec corresponding to an average coverage of about 3.3. (Note that different decisions could be made if the tank were tailored to a specific fuel condition.)

To estimate the door area to provide a 265-gal/sec average flow, we will assume that the average fluid velocity is one-half the peak velocity, or

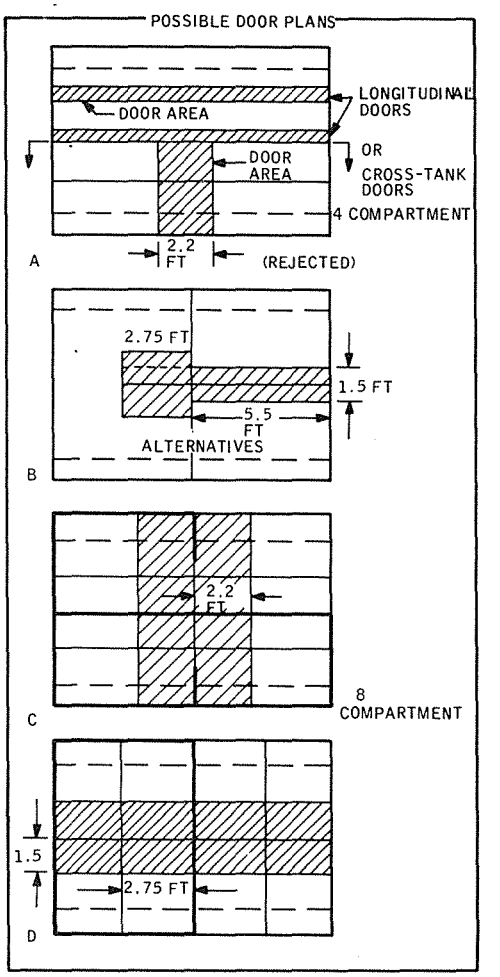
$$\text{Velocity } V_E = 1/2\sqrt{2\,gH} = \sqrt{\frac{2 \times 32.2 \times 4.4}{2}}$$
$$= 8.4 \text{ ft/sec}$$

$$\text{Average Flow (ft}^3\text{/sec)} = \text{gal/sec} \times 0.13368$$
$$= 35.4 \text{ ft}^3\text{/sec}$$

$$\text{Door Area} = \frac{\text{ft}^3\text{/sec}}{\text{Ave fluid velocity}} = 4.22 \text{ ft}^2$$

Since the total door area of our tank plan is 82.5 ft^2, the average compartment plan area is 20.6 ft^2 (four-compartment) or 10.3 ft^2 (eight-compartment). The desired door area is about 20 percent or 40 percent of the available area, respectively.

Possible door plans are next evaluated for performance requirements. Of these, the side-by-side organization of four compartments is not acceptable. If the doors are along the length of the tank, they are too widely separated and too thin to provide proper addition. We will also reject the cross-tank doors of plan A to avoid the fast breakup condition with wide separation.



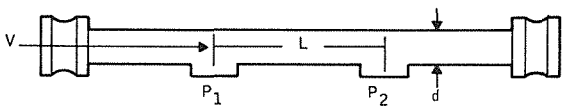
The remaining plans (B, C, and D) appear to meet the basic requirements for performance. Note that the eight-compartment arrangements can be viewed as two smaller tanks. This does not impose problems with the P2V in retaining safe center-of-gravity limits. This possibility should be checked, however, if there is any doubt for a specific aircraft.

Any of the acceptable door plans could be used, leaving the selection to other engineering or design related decisions.

Step 7 — Design the Tank Filling System

Airtanker requirements specify that the tanks be filled from single or dual Kamlock fittings (or equivalent) on either side of the aircraft (or from the tail) at an average fill rate of no less than 500 gal/min. In addition they shall be amenable to offloading through a similar fitting.

The requirements assure tank compatibility with ground loading stations. Ground loading stations are not standard, however. Fill rate, retardant types, densities, and viscosities vary from site to site. These factors determine the pressure drop through a pipe. As a result, in some loading systems the near compartment will fill and pressurize before the far compartment fills. The equations governing this phenomena show that the tank designer can only control pipe length and diameter. Thus, the fill problem can be resolved by providing equal lengths of pipe to each compartment regardless of the direction of fluid flow.



$$\text{Head Loss} = \frac{32\,\mu\,L\,\bar{v}}{P\,g\,d^2}$$

μ = absolute viscosity
L = length
$\bar{v}$ = average velocity
P = fluid density
d = pipe diameter

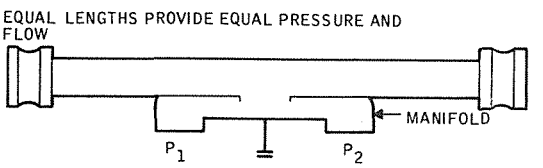
The filling system will normally consist of a fill pipe distribution system and/or a series of one-way flow valves between compartments that in turn may dictate the order of compartment release. Losses in the pressure head across in-wall valves will be minor if the valve area is kept large (3 to 4 times) the area of the pipe inlet.

General Layout Principles — The combined use of intercompartment valving and fill-distribution system provides some efficiencies in achieving offload requirements. Since drainage (from the bottom of the tank) can be accomplished from one downstream valve in each set of compartments, the in-compartment valves also minimize the weight allocated to plumbing.

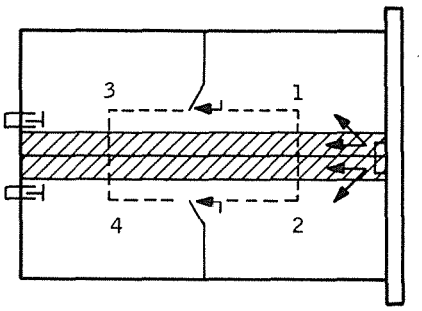
In the example designs there are no difficulties in achieving fill while preserving acceptable concise release volumes. In some cases this system might eliminate otherwise acceptable tank plans. Center-of-gravity permissivity with the P2V allows open choices of release order.

Flow direction was selected as fore-to-aft since the tank's static ground attitude slopes slightly toward the tail. This is the preferrable drainage direction. Location of the fill ports are arbitrary, with loading either from the bottom or the top. Bottom loading from the front is preferred for this tank due to the low extension below the aircraft fuselage.

One-way valves are then required at the Kamlock fittings or in the tank. The location immediately behind the Kamlocks is preferred since the fill pipes will then be self capping. No prolonged drainage from fluid in the pipes will occur.

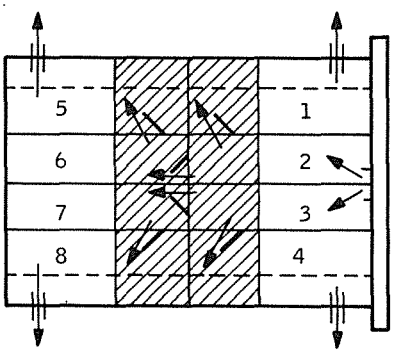


B



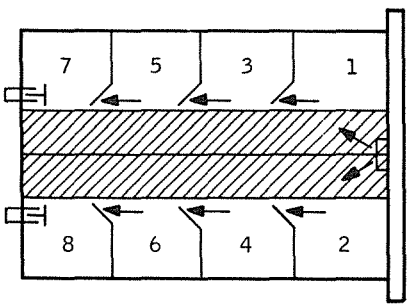
COVERAGE	SEQUENCE
1	1 - 2 - 3 - 4
2	1, 2 - 3, 4
3	1, 2 DELAY 3, 4
4	1, 2, 3, 4

C



COVERAGE	SEQUENCE
1	2 - 1 - 6 - 5 - 3 - 4 - 7 - 8
2	2, 6 - 1, 5 - 3, 7 - 4, 8
3	2,6 delay 1,5 - 3,7 delay 4,8
4	1, 2, 5, 6 - 3, 4, 7, 8

D

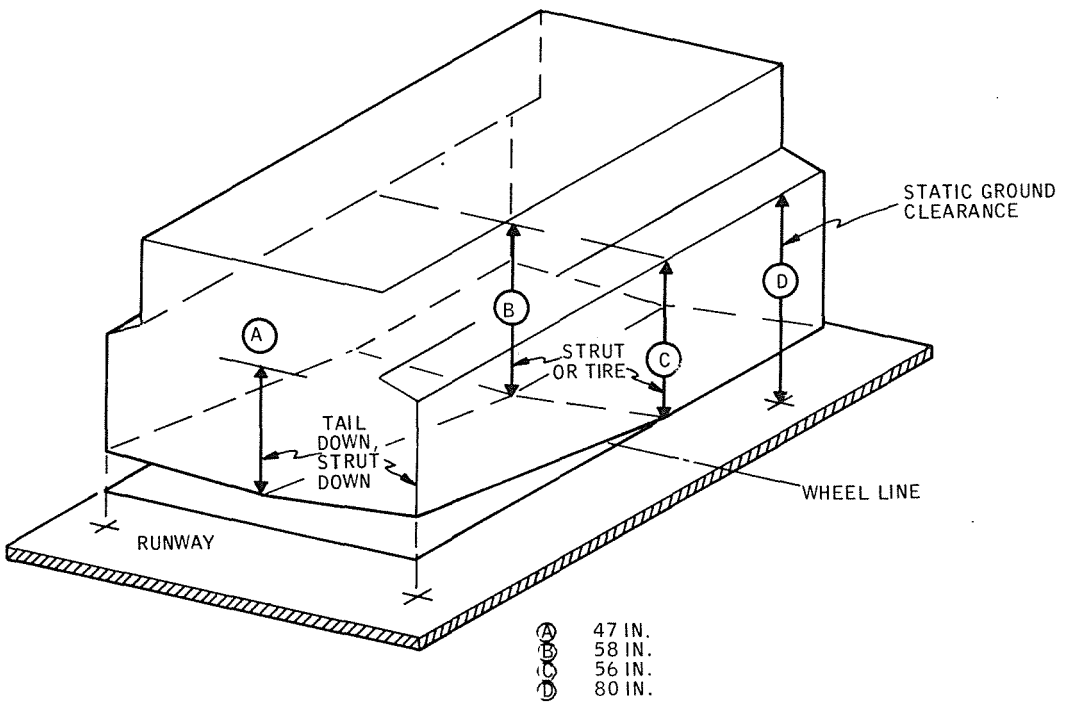


COVERAGE	SEQUENCE
1	1 - 2 - 3 - 4 - 5 - 6 - 7 - 8
2	1, 3 - 2, 4 - 5, 7 - 6, 8
3	1,3 delay 2,4 -5,7 delay 6,8
4	1, 2, 3, 4 - 5, 6, 7, 8

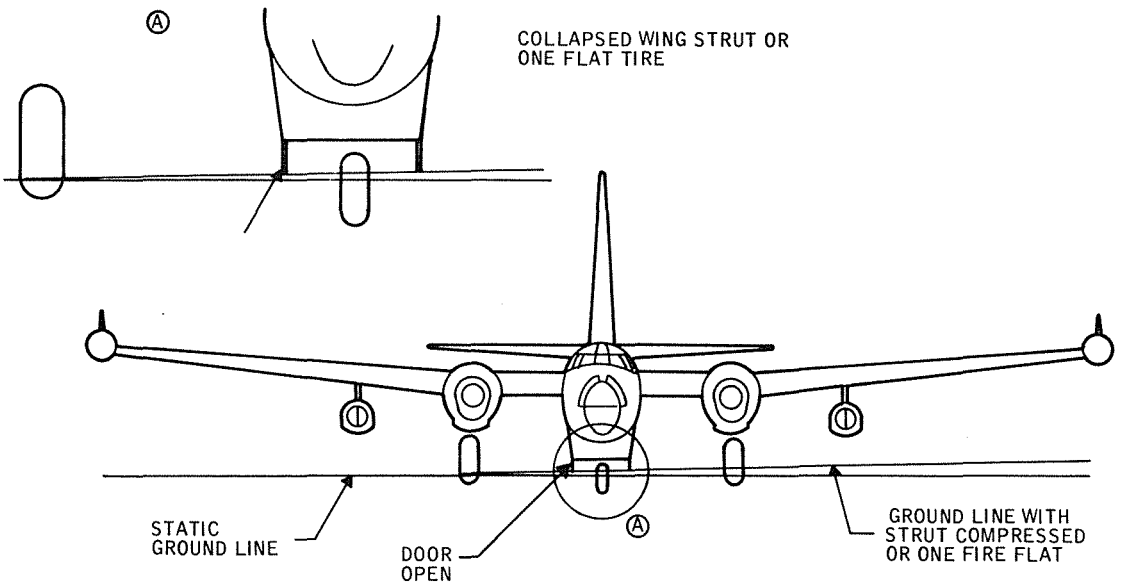
Step 8 — Determine Ground Clearance

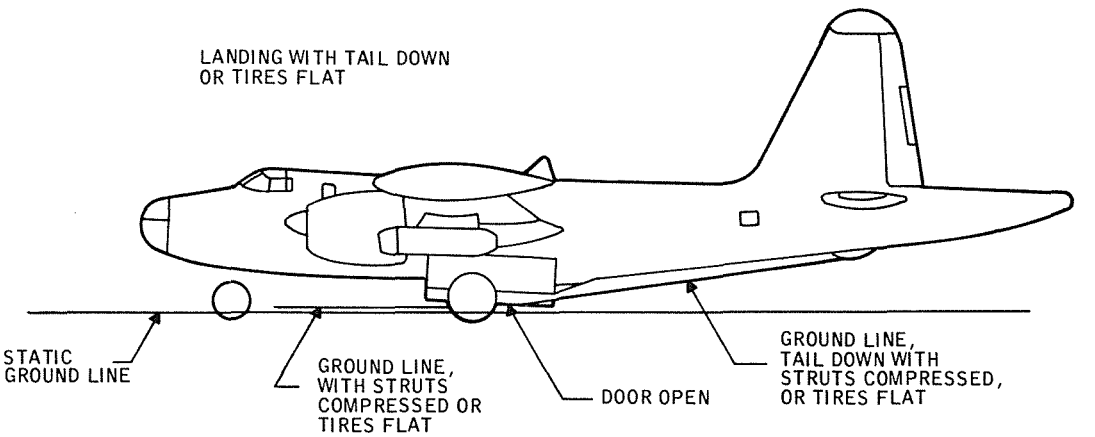
If the tank envelope extends close to the runway, safety clearances must be determined. It is obvious that the open doors must clear the runway for normal maintenance. It is desirable that, given a door-open failure, landing can be safely accomplished with some sequence of other failures that affect runway clearance. These are flat-tire, strut-down, and tail-down conditions. If possible, clearance should be provided for any combination of failures. In practice, designs have been based on the proposition that only one of these failures is probable at any one time. An approximate clearance envelope can be constructed from aircraft drawings and translated to the tank as shown.

The door configurations from previous pages can be evaluated in terms of their effect on tank volume. The preliminary analysis shows that only the 18-inch doors on door plan C preclude extending the tank below the fuselage line while meeting the double safety conditions. Therefore, either door plan B or C will allow extension of the tank to the weight limit (2580 gallons of Phos-Chek XA) or 345 ft^3. This yields a new tank height of 55.3 inches for the preliminary design.



Schematic Methods for Determining Door Clearance Requirements





Step 9 — Design Door-Opening System

Requirements specify that the tank shall be capable of sitting in the loaded condition a minimum of one week following loading. In addition, all tank doors must be closeable in flight. The door control system must be operated by the pilot through primary switches on the control yoke or throttle/trim quadrant. An emergency dump system enabling the pilot to dump his complete load in less than 6 seconds must be incorporated independent of the normal dump system so that no major malfunction can render both inoperable.

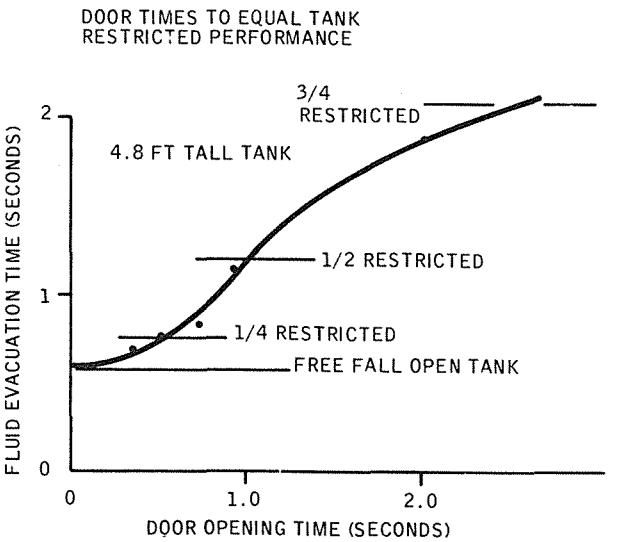
The door system may also be used in controlling retardant flow. These requirements preserve safety regulations and line operations. For the designer they imply that the closed doors must hold without power, and, at minimum, the power system must be able to close the doors against flight loads. There are many options that can meet these criteria. To pursue these options, it is useful to have an understanding of the fluid interaction with the door as it opens.

The performance of the fluid at the door interface for a very fast, powered door, reconstructed from high-speed photographs of the ETAGS static test series is shown opposite. The sequence provides minimum turbulence and side splash that otherwise clouds the view of performance and, as a consequence, allows us to interpret the phenomena as it applies to doors in general.

Door Control Overflow Rate — Door-opening rate can be used to control flow rate as was shown in the ETAGS test series. The principle derives from the fact that volume flow rate is determined by the product of fluid velocity and the effective door area. Thus, a slowly opening door both deflects the fluid slightly and prolongs the flow.

For high-flow-rate drops and to guarantee emergency evacuation times, at least one fast door-rate must be provided. An aternate slow door-rate can, in effect, provide the same flow reduction as a fixed door restriction. The rates to achieve such control are considerably slower than normally applied in tanker design as shown in comparison with a fixed restriction.

To achieve long door-opening times, the doors must be rigid, with sufficient power to hold against the fluid head. Most of the control occurs prior to the time the door reaches 30-degrees open. It is clearly possible to achieve both high flow rates (from fast door opening) and low flow rates (slow opening) in the same door system.

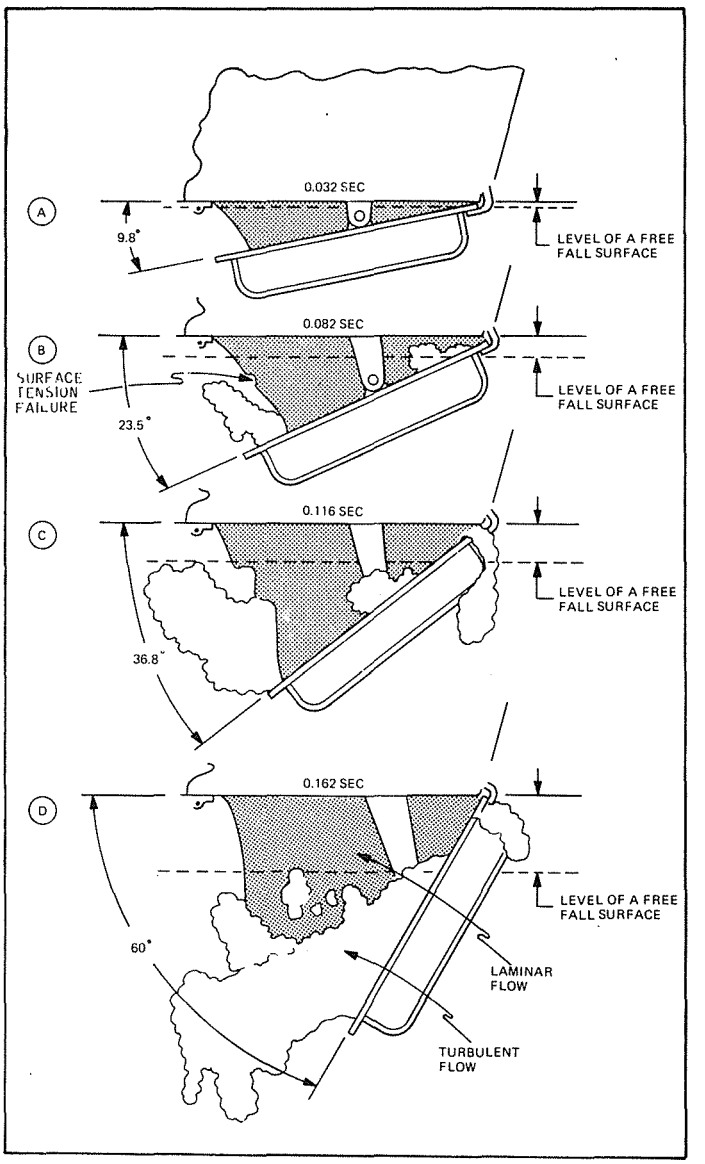


(A) The fluid at the base of the tank falls at or slightly less than free-fall velocity. In the initial period the angular rate of the door runs ahead of the fluid over most of its length. It actually pulls against surface tension, forming the curve on the face of the fluid. Even in a door free to fall as driven by the fluid, the tip farthest from the hinge will attempt to exceed the free-fall velocity of the fluid. As a result, the door will open at a rate that balances fluid resistance acting on a long moment in front of the door's center of gravity, with the fluid's inertial forces acting aft of the door's center of gravity. As a result, a free-fall door is held back by the fluid and opens slightly slower than would be predicted by free-fall calculations alone.

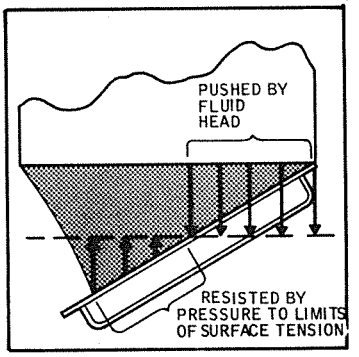
(B) Surface tension failures in the fluid develop at the front edge. Turbulence starts near the hinge where the fluid's free-fall surface pushes against the door.

(C) The plume off the door tip increases, and the turbulence moves down the door.

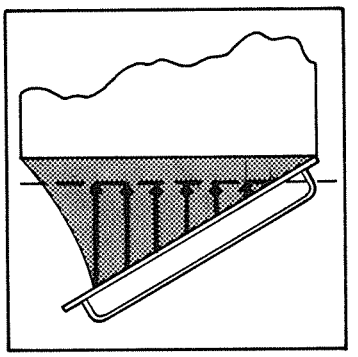
(D) As the door approaches the full-open position, turbulence emanating in the restricted area flows over the bell crank, obscuring the detachment area. Note however, that only the plume has dropped below the tip of the door.



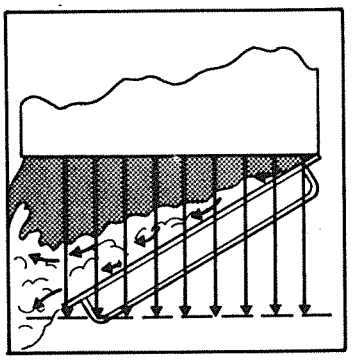
A gravity drop door operates at a rate that balances fluid surface and inertial forces. It defines the natural rate of door opening.



A door that restrains the fluid requires substantial power to react the hydraulic head.



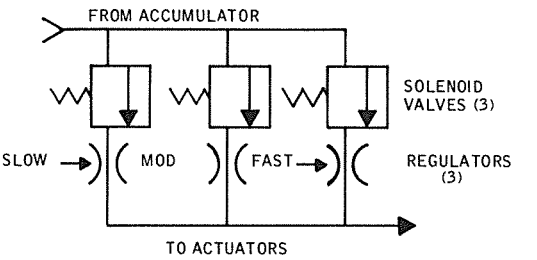
A door that exceeds the natural rate must use considerable power to pull away from the fluid surface...



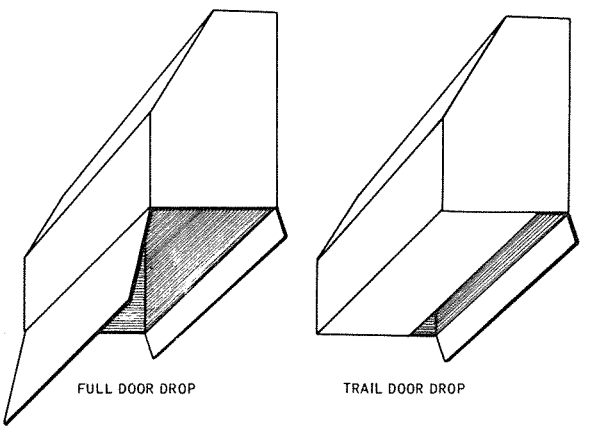
Variable-Rate Doors — Door control of flow rate can be achieved by:

- Changing the door-opening rate
- Changing the open angle

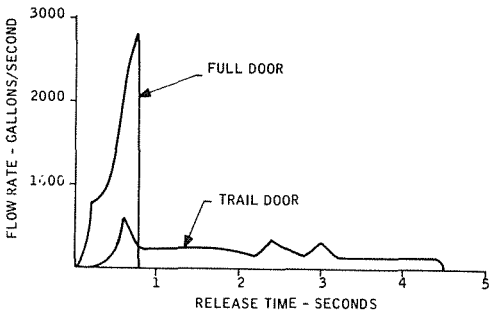
The option to change the door-open angle dynamically is difficult to mechanize since the stroke of a hydraulic or pneumatic system is usually fixed and snubbed by the cylinder. By contrast, the mechanism to control opening rate is relatively simple. The disadvantages of the system, increased complexity, is offset in high-capacity tanks that can only be divided into two compartments by provision of more than two pattern control levels.



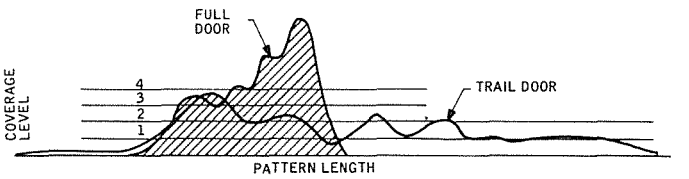
Multiple-Door Compartments — It is also possible to provide control options by offering a choice of door areas used in the drop. Depending on the desired pattern level either the full door or a door representing some smaller fraction of the compartment bottom can be selected.



Flow rates available from one compartment with two door options...



...yield two types of ground pattern.

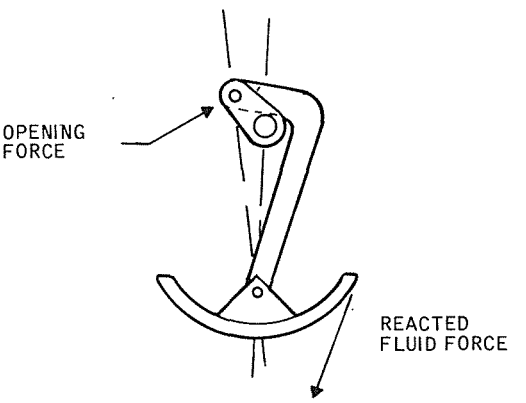


Additional Door Considerations — Other considerations in door and door-opening design are discussed in the following:

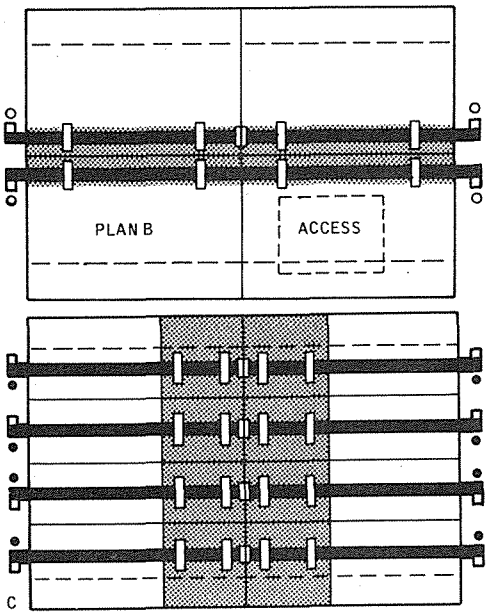
- **Rigid or Flexible?** — In early designs, doors were basically rigid. Such a door offers the possibility of controlling flow rate by changing the rate of door opening; i.e., the door can hold back the fluid. Some of the rigid doors do this, not so much by design intent as by the rate capacity of the power system. Many of the newer door systems are flexible even to the extent of employing a floating hinge with a self-centering scheme of closure. The advantage is that the flexing helps make the seal. As a consequence, better seal integrity and less seal maintenance can be claimed. Such doors cannot be expected to hold against a flow rate and should therefore be designed to open quickly.

- **Gravity Drop Doors** — A few door systems simply release a lock and allow the doors to free fall. The drive mechanism is then primarily a means to close the doors after a drop. Most doors, unless rigid and equipped with a substantial power system, will tend to approximate a free-fall opening curve. For this reason a free-fall opening curve is useful as a first approximation in tank design studies. If the doors are not required to restrain flow, opening rates should be designed to this rate.

- **Locking Techniques** — The requirement to hold retardant without power requires a latching drive mechanism. This feature is usually supplied by an over-center mechanism. In this technique fluid force on the door tends to hold the door mechanism in the closed position. The initial opening force must then move the mechanism back over-center prior to driving the door open.

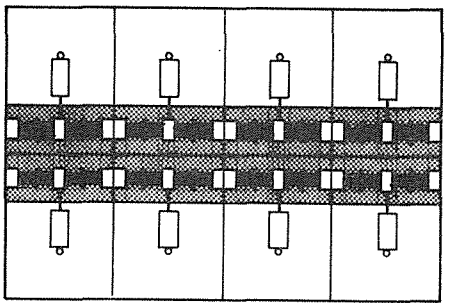


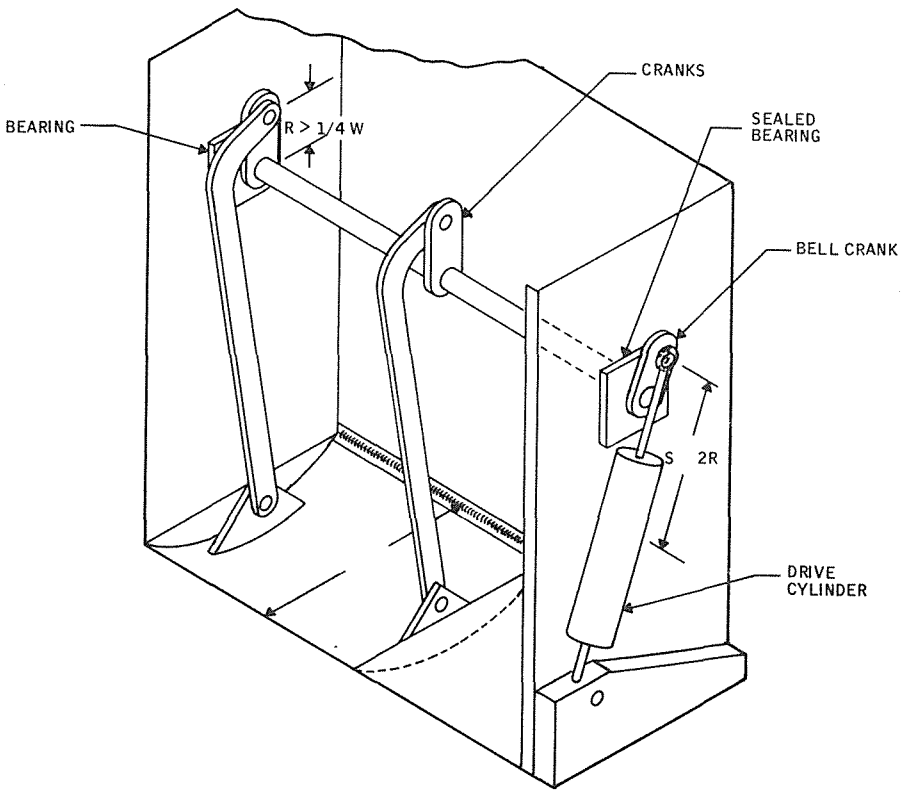
Door Plan Re-Evaluation — An engineering evaluation of the door plans presented shows that none of the tanks yields to straightforward door-opening systems. Both plans B and C can be tanked with a typical torque tube drive system with one hydraulic or pneumatic cylinder for each separately releasable compartment.



These plans produce no unusual difficulties, although access panels should be provided in plan B to permit inspection or repair of the mechanism. Flow interference from locating the mechanism in the fluid is not significant as demonstrated in the ETAGS tests where restrictions up to one-fourth of the tank bottom did not significantly affect flow.

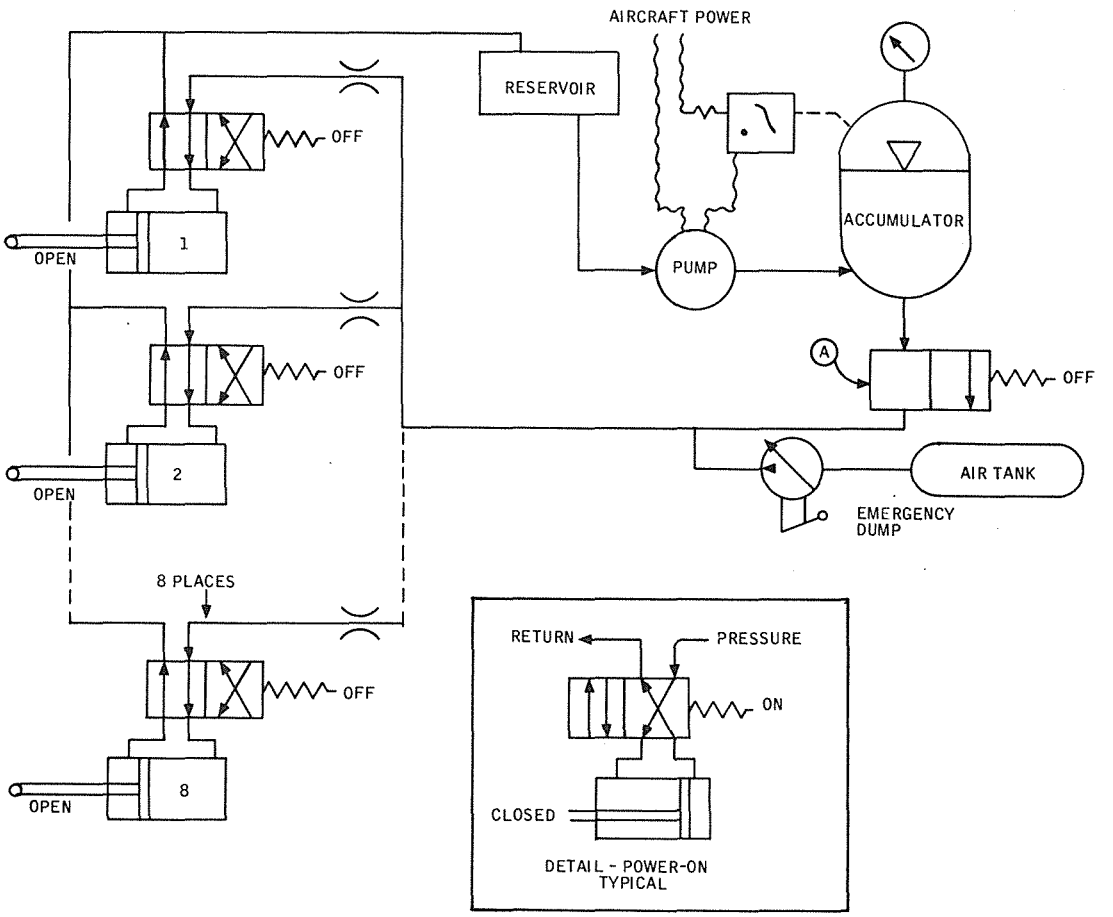
Plan D is more difficult to mechanize, requiring the actuators to be located in the fluid. There is thus complex routing of fluid lines. This complexity results partly because access routes are not accessible for tubing inspection or replacement when the tank is in the aircraft unless they are carried below the fuselage. The plan is rejected primarily on this basis.





Door Control System Design — The selection of hydraulic or pneumatic drive power for the doors is up to the individual designer since no fundamental advantage results from either selection. **It is more important to size the system lines, accumulator and pump with sufficient margin that the design rate is independent of the number of doors opening or the sequence of operation.** (This is a common problem in many existing airtankers.) It is important in this regard to size the system for the appropriate volume and pressure. Information on the design of these systems can be found in any textbook on hydraulic/pneumatic design. Gravity-drop doors are also acceptable, but nonetheless require a system to close them in flight.

The basic schematic shows a typical system. Solenoid valves with flow regulators operate each power cylinder. An electrically controlled switch valve changes return (low-pressure) and power (high-pressure) lines to close the doors. To meet emergency dump requirements independent of aircraft power, these valves should drive tank doors open in the power-down condition. Valve A (closed in the power-down) prevents dumping an over-center lock when the aircraft turns off power after an aborted flight. With power failure, emergency dump is accomplished by blowing the system with a stored air bottle. Landing will occur in the door-down condition, and the system must be bled before operations can be resumed.

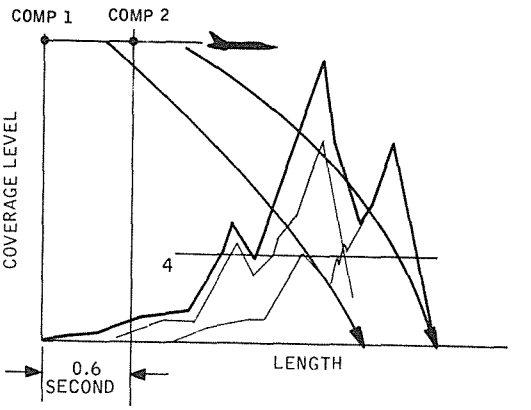


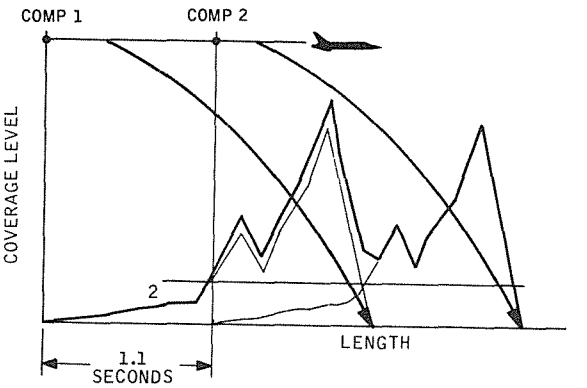
Electronic System — Tanker requirements specify an accurate (±0.1-second), continuously variable intervalometer capable of sequencing doors to provide sequential drops of 1, 2, 4, 6 or 8 compartment combinations.

The electronic control system must allow pilot selection of coverage level and the amount to be released in the drop. Tank sequence, relating to the fill system design or compartment pairing rules, should be automated by the logic. A third option should allow the selection of a time delay to control the sequential release of tank compartments. For the example, P2V tank variable intervalometer settings are not particularly effective because the flow rate is controlled to near uniform over the drop. The delay between tanks is basically constant at 0.6 second, the time from door opening to peak flow rate. This allows continuation of the near constant flow throughout the drop. For tanks with less uniform distributions, some variation in times should be provided. Actual time settings for specific coverage levels are difficult to predict without simulation or test. Therefore, provisions for varying the delay should be provided until experience determines the appropriate setting.

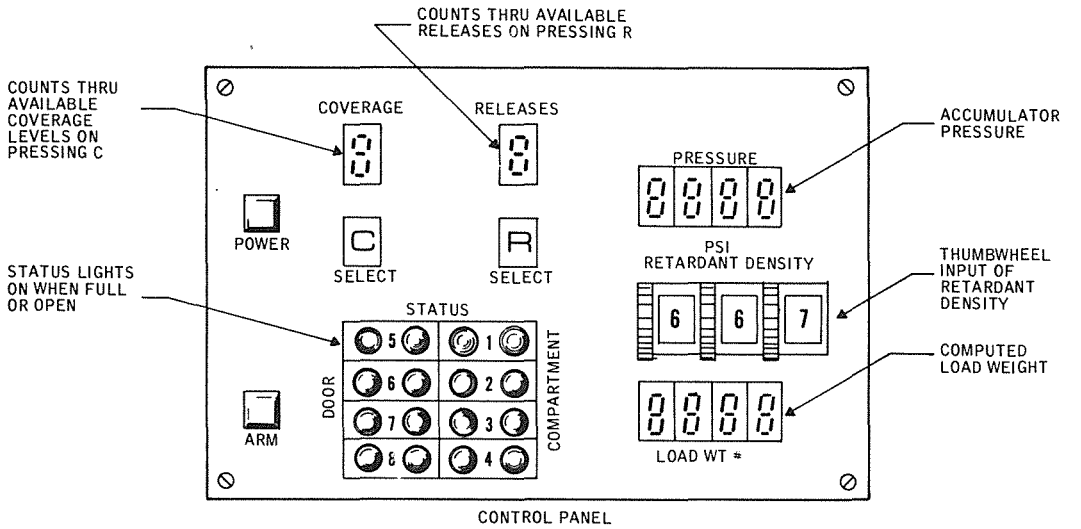
In most cases, the most efficient use of multiple-compartment drops occurs when individual releases are spaced along the aircraft flight path. The appropriate delay interval will vary with drop height, aircraft velocity, retardant type, and the desired coverage level.

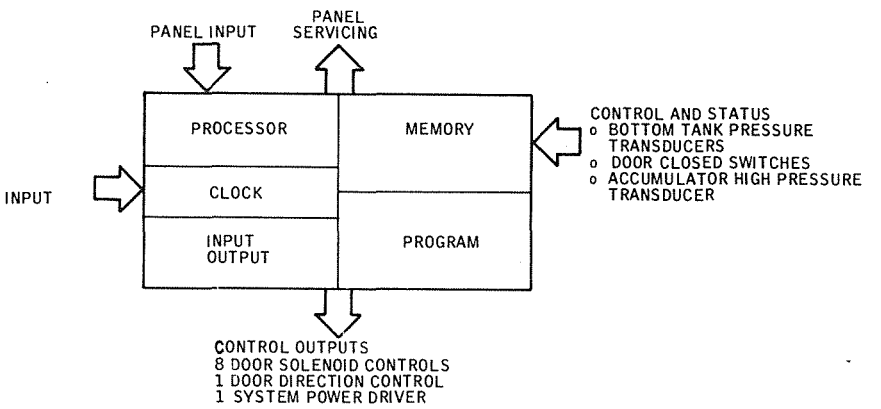
The simplest technique of selecting a drop plan is to allow the pilot to plan the drop in advance by cockpit switch selections.





Example Door Control System — With the eight-compartment tank design, hardwire logic is at best complicated. The availability of reliable and inexpensive microcomputer hardware provides a more up-to-date approach. The system is programmed in advance by Read Only Memory that can be changed if experience shows different constants or sequences are more desirable. The system has the ability to service other tank features, such as fill indicators and status. The design is within the capability of many small shops. One such system is shown below for the eight-compartment plan. Note that the system has the capability of accommodating further drop automation or status monitoring if desired.





Step 10 — Design the Venting System

Tanker requirements state that vents shall not allow slosh-over or leakage during takeoff or landing and that negative pressures developed during release shall not cause pop-bottling. Door area to vent area should not exceed 10:1, or the in-flight negative pressure must not exceed 0.25 psi.

Negative pressures develop in the tank as air rushes in to replace the fluid volume leaving the tank. The pressure drop is a direct function of the square of the air velocity through the vent:

$$P = 0.000013\ V_{air}^2$$

where pressure is in pounds per square inch and air velocity in feet per second.

The peak air velocity can be estimated by multiplying the peak fluid velocity by the door-to-vent area ratio. This area ratio must be picked to represent the smallest area traversed in the venting system. For the example tank, peak velocity is:

$$V_E = \sqrt{2gH} = \sqrt{2g\ 4.5\ ft} = 17\ ft/sec$$

Door area is:

20% of 82.5 ft² = 16.5 ft² (4-compartment plan)

40% of 82.5 ft² = 33 ft² (8-compartment plan)

To hold a pressure of 0.25 psi, air velocity must be held less than:

$$V_{air} = \sqrt{\frac{P}{0.000013}} = \sqrt{\frac{0.25}{0.000013}} = 137\ pfs$$

The vent area must then exceed:

$$A_{fluid}A_{door} = 137\ pfs,\ A_{vent} = \frac{V_{fluid}A_{door}}{137}$$

For the four-compartment plan:

$$A_{vent} = \frac{17.2 \times 16.5}{137} = 2.1\ ft^2$$

For the eight-compartment plan:

$$A_{vent} = \frac{17.2 \times 33}{137} = 4.14\ ft^2$$

Door area to vent area ratios are therefore 8:1.

These values will increase if (a) the vent stack is very long due to friction in the stack, (b) if the tank volume is large compared with fuselage volumes available for venting, or (c) if anti-splash valves have heavy resistance springs.

In exploring the possibility of using ram air for venting purposes, it was noted that ram air at typical flight velocities provides a pressure of 0.3 to 0.5 psi positive pressure depending on the altitude and velocity. The difficulty in using this air source is that tank pressures depend on volume flow. Consider that, at 125 knots, an air velocity of 211 ft/sec will impinge on an air scoop. To provide zero tank pressure

Area scoop × 211 = fluid velocity × area door

Thus, in our examples:

$$\text{Scoop area} = \frac{17 \times 16.5}{211} = 1.3\ ft^2\ (4\text{-compartment})$$

$$= \frac{17 \times 33}{211} = 2.66\ ft^2\ (8\text{-compartment})$$

Greater areas must be provided to accommodate ductwork friction if it is of any significant length. Note that any restriction in the duct work prior to tank entry will produce a pressure drop in the tank. This technique is useful as long as proportional areas are maintained. This positive pressure will slightly increase flow rates, particularly where the single compartment rather than the total door area is used for a fixed scoop area.

Pressure drop due to wall friction may be calculated from the equation:

$$P_{psi} = \frac{0.00278L\ Q^2}{D^5}$$

where Q = volume flow rate, L = vent length, D = vent diameter.

The small positive pressures available from dynamic pressure are generally difficult to use because of the necessity to preserve an adequate volume flow in

ductwork from the scoop of the top of the tank. In the example tank, retardant flow is restricted by intent through reduced door areas, considerably reducing scoop area over that of a typical free-fall tank. In general it is more practical to provide an adequate unrestricted air supply (static pressure) than attempt to extract the small potential available from ram air (dynamic pressure).

Fill Venting and Tank Venting — If it is possible to run a stack vent sufficiently tall to prevent slosh-out and with enough flow to a vent port external to the aircraft, the tank venting and fill venting can be operated in common. This form of venting is desirable in that it also releases retardant fumes from cockpit and personnel areas. If it is not possible, primary vents must be capped with splash valves and a secondary, much smaller vent system must be provided to relieve pressure during tank filling. A minimal clearance at the top of each compartment with a small (2- to 3-inch) plastic hose to the exterior of the tank will suffice for this purpose. The cross-compartment openings will not normally reduce capacities significantly nor, under most flight situations, cause much flow-through to adjacent tanks.

Venting is somewhat difficult in the P2V although cabin volume is generally large enough with proper ventilation to support tank evacuation. The major problem resides in finding space above the tank, between structures, to provide adequate stack venting. For this reason, one flapper valve vent for each tank would be located near the forward end of the tank, allowing draw from the radar compartment, and near the aft of the tank drawing through the floor and the tail section. A separate fill vent system from the front of the tank (highest point) will then be run from each compartment at least 3 feet above the tank.

Step 11 — Determine Structure and Fabrication Features

The conceptual design is far from a reality, and must now be designed to meet structural requirements in a manner that yields fabrication techniques. It is not possible in a brief text to fully define this process. Some general guidelines and notes are provided in the following paragraphs on items that are peculiar to retardant tank systems. The preliminary structural analysis will size tank members and, as a result, refine the weight and volume estimates for the tank. Following this step the design process is reiterated in greater detail to confirm or revise preliminary conclusions. Several iterations may, in fact, be required before the design is buildable and fully consistent with objectives.

General Construction — The tank and gating system are basically airframe structures that must meet load conditions typical of the airframe. In other words, the presence of the loaded tank should not compromise the load limits and design conditions of the aircraft. Typical design criteria can be found in MIL-STD

As an airframe structure, aircraft-grade materials should be selected, particularly in structural members and fasteners. In general, riveted structure is preferred. Welding should be limited if possible to areas that are not critical (due to the difficulty of certifying weldments) and where they can be inspected.

Adequate access ports should be provided to allow inspection of structure-critical points and all operating mechanisms. Operating members such as bearings and door hinges should, if possible, be easily replaceable to reduce maintenance difficulties.

Selection of Materials — Fire retardants are salts and, as a result, promote corrosion. The selection of materials and good design practices can minimize corrosion, but not preclude the need for good maintenance. For more detailed information see **User Guideline Manual for Control of Fire Retardant Corrosion,** Ocean City Research Corporation, USDA Forest Service, Northern Forest Fire Laboratory, Drawer G, Missoula, Montana.

Since retardant vapors are themselves corrosive, the aircraft envelope in which the tank is to be placed should be ventilated, amenable to inspection/repair or modified to reroute or replace corrosion-sensitive control elements that might be made inaccessible by the tank installation.

Seals — Door seals are a traditional maintenance problem. They are deteriorated with time by retardant contact, worn by mechanical operation of the doors, and occasionally blown by over pressurization. Some retardants such as Fire-Trol 931-L have been known to dissolve adhesives at the seal attachment points and significantly deteriorate absorbent seal materials. Recent tank designs have solved many of these problems by using a metallic extrusion to hold the gasket material in place. There are also commercially available nonabsorbent rubber or synthetic extrusions that provide a substantial amount of takeup. A properly designed extrusion system is easily replaced if damaged and allows considerable takeup which is important in over-center locking of the doors.

Conversion Factors for Tank Design

To convert A to B multiply by C

A	B	C
Cubic feet	Gallons (U.S.)	7.481
	Gallons (British)	6.629
	Pounds of water	62.369
	Pounds of Phos-Chek	66.735
	Pounds of Fire-Trol	75.878
Feet per second	Knots	0.5921
Feet of water	Pounds per square inch (psi)	0.43352
Feet of Phos-Chek	Pounds per square inch	0.4639
Feet of Fire-Trol	Pounds per square inch	0.4929
Gallons per 100 square feet (gpc)	Inches of water	0.01604
Gallons (U.S.)	Cubic feet	0.13368
	Gallons (British)	0.83268
	Pounds of water	8.337
	Pounds of Phos-Chek	8.921
	Pounds of Fire Trol	9.479
Inches of Fire-Trol	Pounds per square inch	0.04108
Inches of Phos-Chek	Pounds per square inch	0.03866
Inches of water	Pounds per square inch	0.036127
	Gallons per 100 square feet	62.34
Knots	Feet per second	1.689
Pounds per square inch	Inches of water	27.68
	Inches of Phos-Chek	25.87
	Inches of Fire-Trol	24.34
	Feet of water	2.3067
	Feet of Phos-Chek	2.1556
	Feet of Fire-Trol	2.0288
	Pounds per square foot (psf)	144